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CP violation: Recent Results from BABAR

Presented at SUSY2014

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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

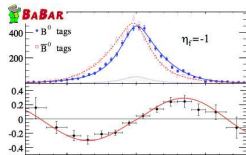
PRL **81** 091801, 2001, Nobel prize 2008 ¹

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)

¹For 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

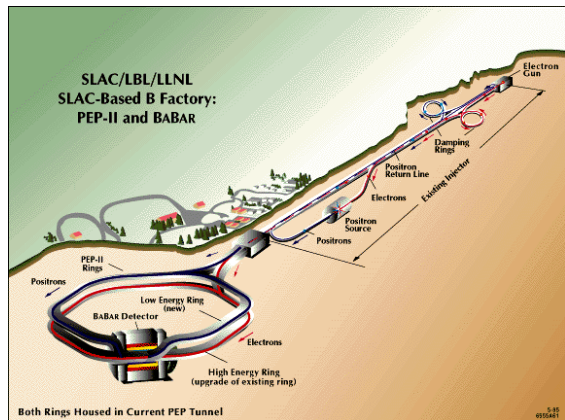
Direct CP violation

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

Interference between mixing and decays

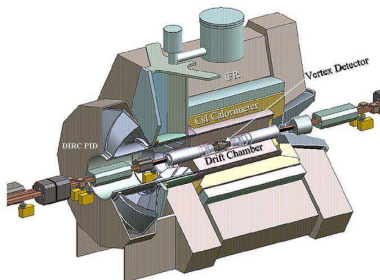
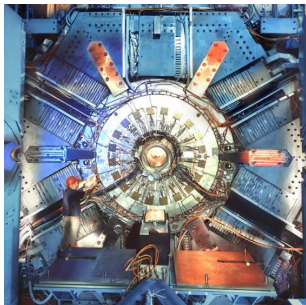
Different time dependence

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 $B^\pm \rightarrow K^{*\pm}(892)\pi^0$

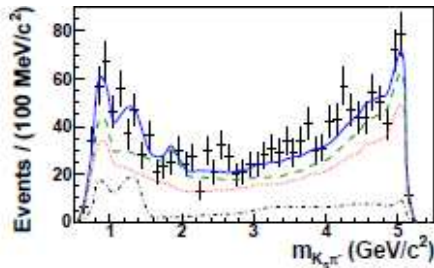
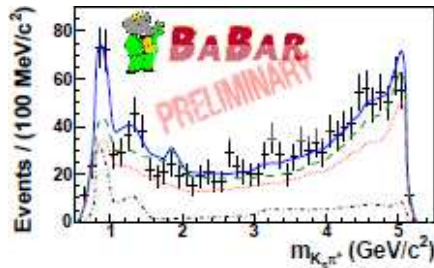
new result - preliminary

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



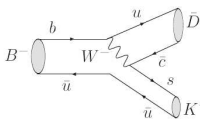
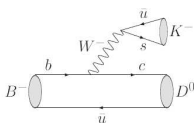
$A_{CP} = -0.52 \pm 0.14 \pm 0.04 \pm 0.04$: Significant at 3.4σ

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 γ

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

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



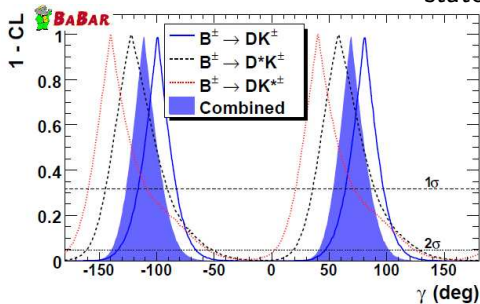
GGSZ: $K\pi\pi$ etc

GL: K^+K^- etc

ADS: $K^+\pi^-$ doubly-

Cabibbo-suppressed

states



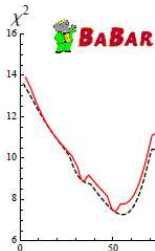
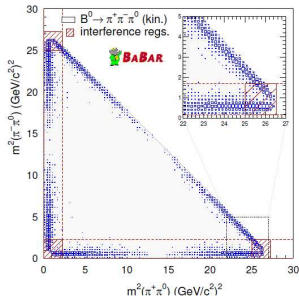
$$\gamma = (69_{-16}^{+17})^\circ$$

Significant at 5.9σ

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

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 α

$B \rightarrow X_S l^+ l^-$ Direct CPV

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

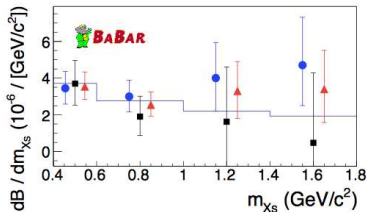
10 different exclusive X_S
modes (K^+ , $K^+\pi^0$, $K^+\pi^-$,
 $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+$, K_S^0 , $K_S^0\pi^0$,
 $K_S^0\pi^+$, $K_S^0\pi^+\pi^0$, $K_S^0\pi^+\pi^-$)

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

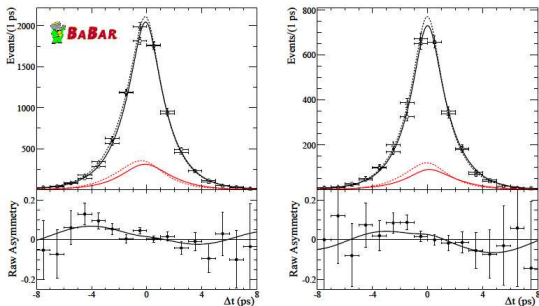
#	Final State	#	Final State
1*	$B^+ \rightarrow K_S \pi^+ \gamma$	20	$B^0 \rightarrow K_S \pi^+ \pi^- \pi^+ \pi^- \gamma$
2*	$B^+ \rightarrow K^+ \pi^0 \gamma$	21	$B^0 \rightarrow K^+ \pi^+ \pi^- \pi^- \pi^0 \gamma$
3*	$B^0 \rightarrow K^+ \pi^- \gamma$	22	$B^0 \rightarrow K_S \pi^+ \pi^- \pi^0 \pi^0 \gamma$
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.



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

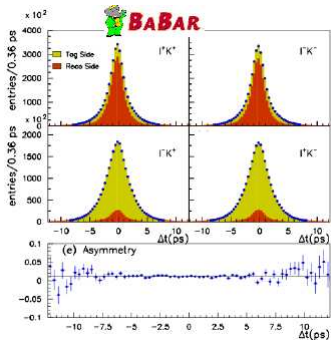
Consistent with $\sin 2\beta$ determined from $B^0 \rightarrow \text{charmonium}$

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(≈ 0). Means the $D\bar{0}$ 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 $K^\pm\pi^\mp$

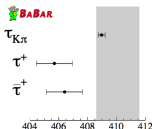
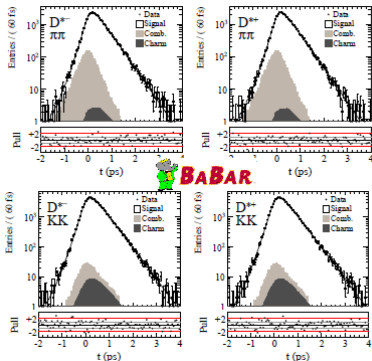
Rate Γ^+ for $D^0 \rightarrow CP_{even}$,

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

Γ for $D^0 \rightarrow CP_{mixed}$

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

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



So 3.3σ 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:

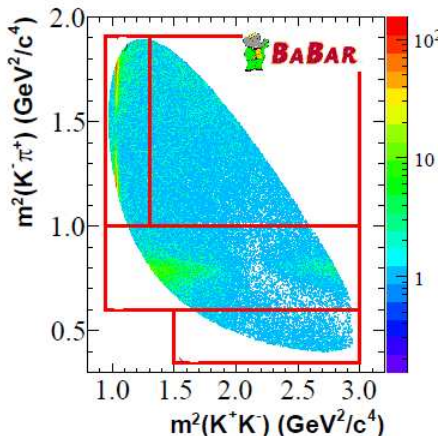
$$A_{CP} = (0.37 \pm 0.30 \pm 0.15)\%$$

Also no sign in any of the subregions

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

or in isobar-model fits

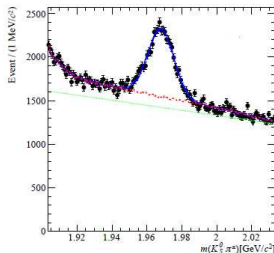
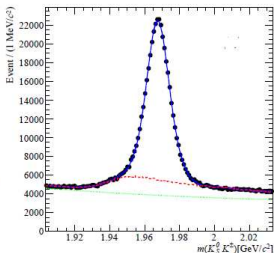
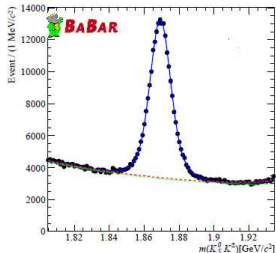
(KK^* , $\pi\phi$, etc)



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 α, β, γ angles.
Powerful constraints on New
Physics models

