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

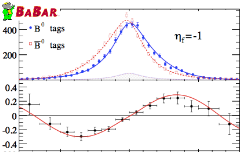
Discovery 1964

Fitch and Cronin (PRL **13**:138, 1964; Nobel Prize 1980)
Small effect (0.3%) for s quark: $K_L^0 \to \pi^+\pi^-$

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

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

PRL **81** 091801, 2001, Nobel prize 2008 [1]
Large effects (several %). Many measurements.
Mainstream $\Upsilon(4S) \to B^0\overline{B^0}$
1st decays to CP eigenstate, 2nd tagged as b or $\overline{b}$
Plot decay time dependences.



BaBar: PRD79:072009,2009

Reported in D mesons (c quark)

[1] 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

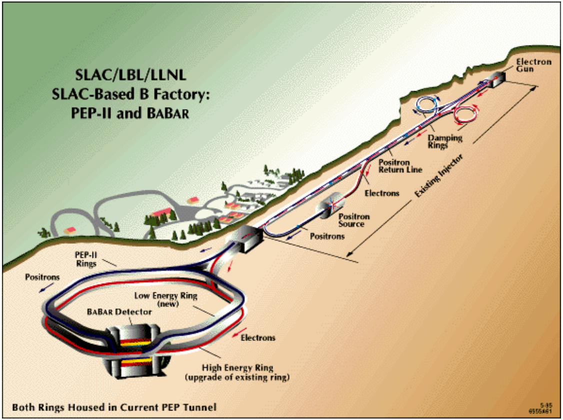
Direct CP violation

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

Interference between mixing and decays

Different time dependence

PEP-II: a 'B factory'

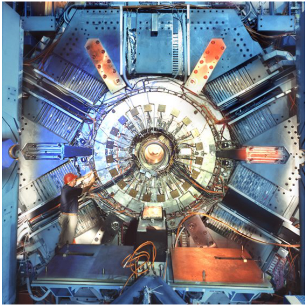


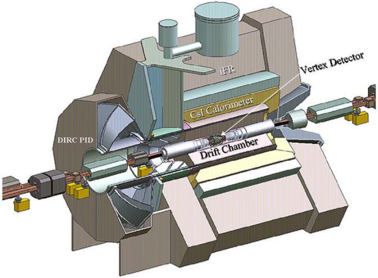
Results from $471 \times 10^6 \Upsilon(4S)$ decays produced with speed $0.5c$ in the lab

Luminosity $1.2 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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 $B^{\pm} \to K^{*\pm}(892)\pi^0$

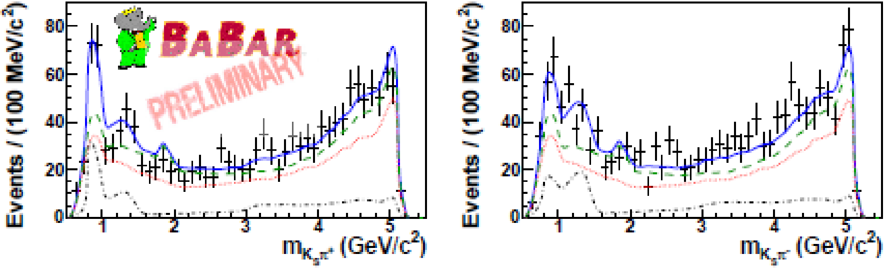
new result - preliminary

Select $B^{\pm} \to K_s^0\pi^{\pm}\pi^0$. 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: $K^{*0}(892)\pi^+, K^{*+}(892)\pi^0, K_s^0\rho^+, etc$



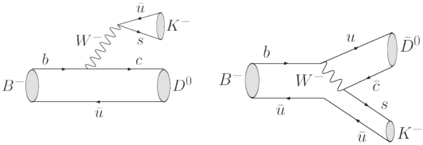
$A_{CP} = -0.52 \pm 0.14 \pm 0.04 \pm 0.04$: Significant at 3.4σ

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

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

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

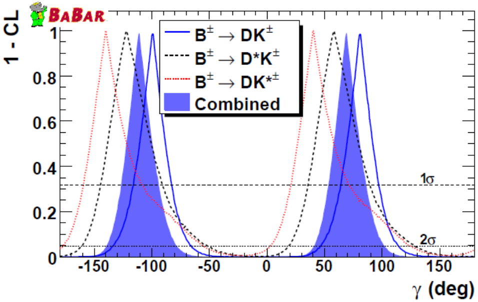
Interference between 2 diagrams in final states accessible through D or $\overline{D}$



GGSZ: $K\pi\pi$ etc

GL: K^+K^- etc

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



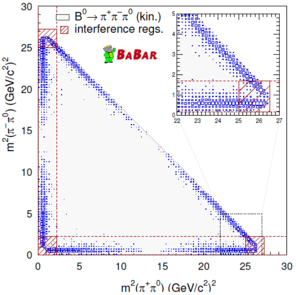
$$\gamma = (69^{+17}_{-16})^{\circ}$$

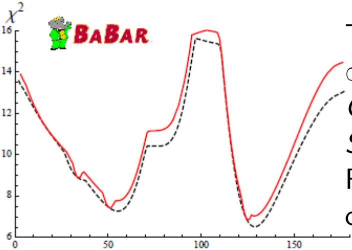
Significant at 5.9σ

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

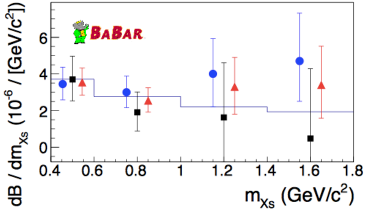
$B \to X_s \ell^+ \ell^-$ Direct CPV

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

10 different exclusive X_s modes ($K^+, K^+\pi^0, K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^-\pi^+, K^0_S, K^0_S\pi^0, K^0_S\pi^+, K^0_S\pi^+\pi^0, K^0_S\pi^+\pi^-$)

Extrapolation gives branching ratio $(6.73^{+0.70}_{-0.64}{}^{+0.34}_{-0.25} \pm 0.50) \times 10^{-6}$ for $m^2_{\ell\ell} > 0.1$

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



blue=electrons,
black=muons,
red=average

$B \to X_s\gamma$ 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.

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

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

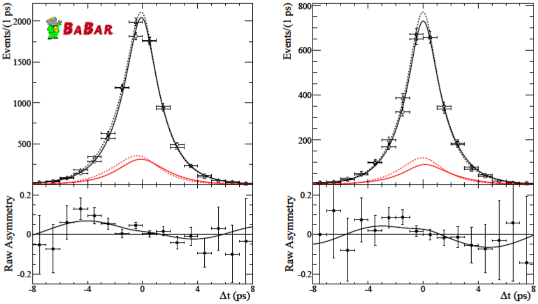
consistent with SM prediction

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

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

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

One D^* reconstructed fully from $D^0\pi$ with $D^0 \to K\pi, K\pi\pi, K\pi\pi\pi, K^0_S\pi\pi$
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.



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

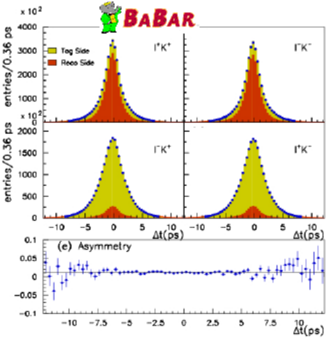
Consistent with $sin2\beta$ determined from $B^0 \to$charmonium

CP violation in mixing: $B^0 \to D^{*-} X \ell \nu_\ell$ 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 DØ result must be due to B_s decays.

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



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

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

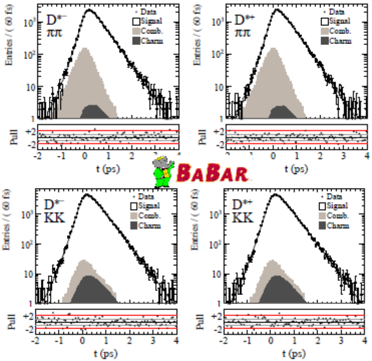
Phys. Rev. D **87** 012004 (2012)

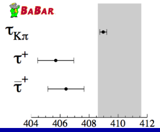
Compare lifetimes to CP even K^+K^- and $\pi^+\pi^-$ with CP mixed $K^\pm\pi^\mp$

Rate Γ^+ for $D^0 \to CP_{even}$,
$\overline{\Gamma}^+$ for $\overline{D}^0 \to CP_{even}$,
Γ for $D^0 \to CP_{mixed}$

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

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





So 3.3σ evidence for mixing, no evidence for CP violation

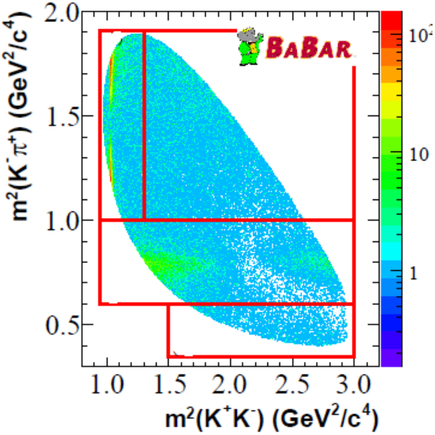
Charm: Singly Cabibbo Suppressed $D^{\pm} \to K^{+}K^{-}\pi^{\pm}$

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

Evaluate charge asymmetry:

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

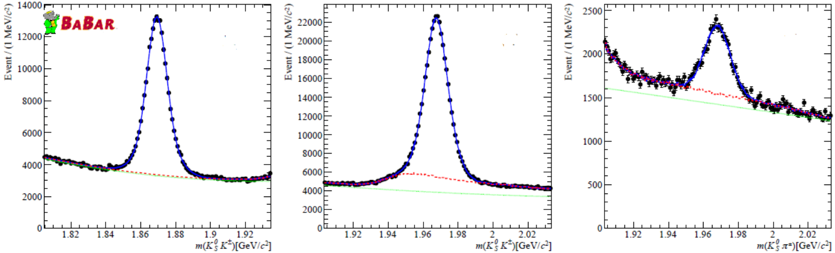
Also no sign in any of the subregions (low $M_{K\pi}$, K^*, ϕ, high $M_{K\pi}$) or in isobar-model fits (KK^*, $\pi\phi$, etc)



Charm: $D^\pm \to K^0_S K^\pm, D^\pm_S \to K^0_S K^\pm, D^\pm_S \to K^0_S \pi^\pm$

Phys. Rev. D**87** 052012 (2013)

Detector charge bias determined from data



$A_{CP}(D^\pm \to K^0_S K^\pm) = (0.13 \pm 0.36 \pm 0.25)\%$
$A_{CP}(D^\pm_S \to K^0_S K^\pm) = (-0.05 \pm 0.23 \pm 0.24)\%$
$A_{CP}(D^\pm_S \to K^0_S \pi^\pm) = (0.6 \pm 2.0 \pm 0.3)\%$
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