Recent BaBar results on CP violation in B-meson decays

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1. BaBar detector
2. CP asymmetries with inclusive dilepton measurement.
3. CP asymmetries in FCNC:
   - $b \to s\gamma$
   - $b \to s\ell\ell$

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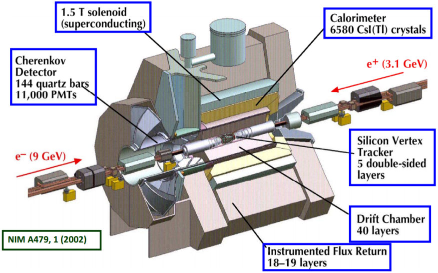
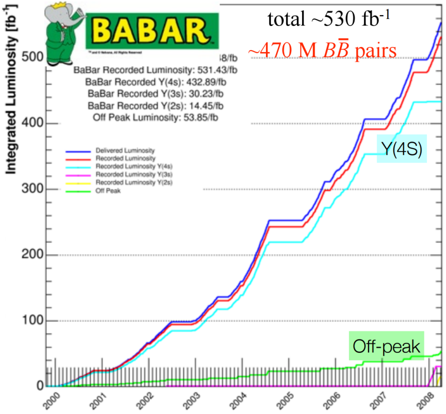
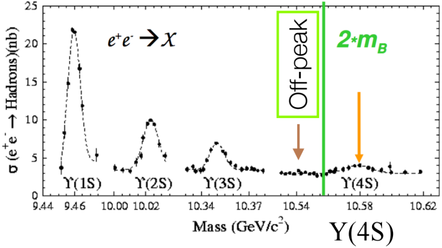
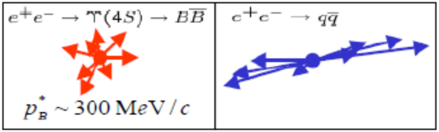
- PEP-II, an asymmetric e^-e^+ collider.
- Operating mostly at $\Upsilon(4S)$ threshold.

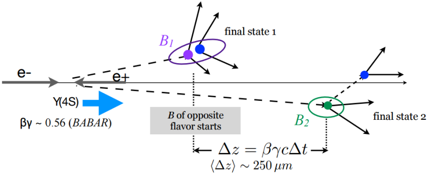








- B mesons produced in a clean environment.
- Just above the $m(B\overline{B})$ threshold.



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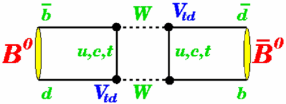
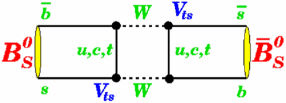
$B^0\overline{B}^0$ mixing

- Neutral mesons couple to their anti particles via weak interactions.

- $B^0 \Leftrightarrow \overline{B}^0$, $B^0_s \Leftrightarrow \overline{B}^0_s$, $D^0 \Leftrightarrow \overline{D}^0$, $K \Leftrightarrow \overline{K}^0$.
- We can writhe the weak eigenstates as:

$$|B_{L/H}\rangle = \frac{1}{\sqrt{p^2+q^2}}(p\,|B^0\rangle \pm q\,|\overline{B}^0\rangle)$$





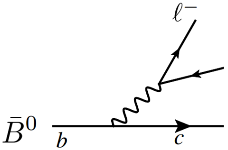
- Then the CP asymmetry can can be written as:

$$A_{CP} = \frac{\mathcal{P}(\overline{B}^0 \to B^0) - \mathcal{P}(B^0 \to \overline{B}^0)}{\mathcal{P}(\overline{B}^0 \to B^0) + \mathcal{P}(B^0 \to \overline{B}^0)} \approx 2(1 - |\frac{q}{p}|)$$

- $\Upsilon(4S)$ has an anti-symmetric state:
  $\frac{1}{\sqrt{2}}(B^0(t_1)\overline{B}^0(t_2) - \overline{B}^0(t_1)B^0(t_2))$
- One B is a specific flavour state tags the other one.

Inclusive dilepton measurement

- B mesons decay in $\sim 10\%$ semileptonically.
- Charge of lepton determines the B meson flavour.
- If one observes same sign leptons $\rightarrow$ mixing occurred ($\ell\ell \in \{ee, \mu\mu\}$)
  - $\ell^-\ell^+$: no mixing
  - $\ell^-\ell^-$: $B^0 \rightarrow \overline{B}^0$.
  - $\ell^+\ell^+$: $\overline{B}^0 \rightarrow B^0$.



- Writing down the mixing probabilities (time integrated):

$$\mathcal{P}^{\pm\pm} \propto (1 \pm A_{CP})\chi_d$$

$$\mathcal{P}^{\pm\mp} \propto (1 - \chi_d),$$

where A_{CP} is the CP asymmetry and χ_d is the effective mixing probability.

- SM: $A_{CP} \sim \mathcal{O}(10^{-4})$

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Detector effects

- Detector is not a perfect device $\rightarrow$ Introduced charge asymmetries a_{ℓ_j} for each ℓ_j.
- $\Upsilon(4S)$ also goes to $\mathrm{B^+B^-}$. Contribution: $r_B = N_{\mathrm{B^+B^-}}/N_{\mathrm{B^0\overline{B}^0}}$.
- Time integrated probability gets modified:

$$\mathcal{P}^{\pm\pm} \propto (1 \pm a_{\ell_1} \pm a_{\ell_2} \pm A_{CP})\chi_d$$
$$\mathcal{P}^{\pm\mp} \propto (1 - \chi_d + r_B)(1 \pm a_{\ell_1} \mp a_{\ell_2})$$

- Summing over all events in $\ell_1\ell_2 \in \{\mathrm{ee}, \mathrm{e}\mu, \mu\mathrm{e}, \mu\mu\}$ categories:

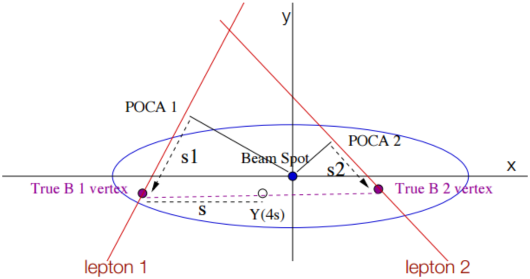
$$N^{\pm\pm}_{\ell_1\ell_2} = 1/2 N^0_{\ell_1\ell_2}(1 \pm a_{\ell_1} \pm a_{\ell_2} \pm A_{CP})\chi_d^{\ell_1\ell_2}$$
$$N^{\pm\mp}_{\ell_1\ell_2} = 1/2 N^0_{\ell_1\ell_2}(1 - \chi_d^{\ell_1\ell_2} + r_B)(1 \pm a_{\ell_1} \mp a_{\ell_2})$$

- We have 16 observables, and 13 unknowns. a_{ℓ_j} highly correlated.
- Adding additional observable: events containing only single electron (a_e).
- 17 observables as input to χ^2 fit, extracting: A_{CP}, 4 signal yields, 4 efficiency asymmetries, 4 mixing probabilities.

Event selection

- Item select an isotropic events with $\geqslant 4$ tracks.
- Each lepton track should have $p > 0.6$ GeV/c.
- Hard requirements on the e, μ PID selection.
  - $\epsilon_e \sim 93\%$, ϵ_μ $40 - 80\%$.
  - MissID: $\mathcal{P}(h \to e) < 0.1\%$, $\mathcal{P}(h \to \mu) \sim 1\%$.
- Veto J/ψ, $\psi(2S)$ and photon conversion.

- Δt is calculated from the separation of the two POCAs along the beam direction and the c.m. boost ($\beta\gamma = 0.56$).
- $\Delta t < 15$ ps and $\sigma \Delta t < 3$ ps



Systematics

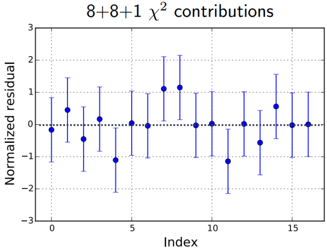
Source	(10^{-3})
Generic MC bias correction	1.04
MC branching fractions	0.43
Fake lepton corrections in dilepton	0.77
Fake e correction in single electron	0.65
Neutral/charged B difference	0.74
Direct-/cascade e asymmetry difference	0.44
Direct-/cascade μ asymmetry difference	0.34
Background-to-signal ratios	0.68
Random forest cut efficiency	0.08
Total	1.90

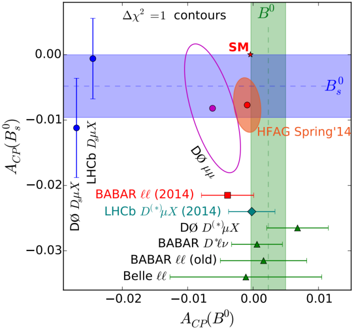
- Dominant systematic from bias in MC.
- Secondly the MC/data corrections to PID.
- Difference in charge asymmetry between B^0 and average of B^0 and $B^{\pm}$.

Fit results

$A_{CP} = (-3.9 \pm 3.5) \times 10^{-3}$ PRL 114, 081801 (2015)

N^0_{ee}	$N^0_{e\mu}$	$N^0_{\mu e}$	$N^0_{\mu\mu}$
430875 ± 515	365343 ± 429	458200 ± 480	268077 ± 381
χ_d^{ee}	$\chi_d^{e\mu}$	$\chi_d^{\mu e}$	$\chi_d^{\mu\mu}$
0.2248 ± 0.0006	0.1769 ± 0.0006	0.1754 ± 0.0005	0.2032 ± 0.0007
a^{e1}	a^{e2}	$a^{\mu 1}$	$a^{\mu 2}$
0.0034 ± 0.0006	0.0030 ± 0.006	-0.0056 ± 0.0011	-0.0065 ± 0.0011





- Result $A_{CP} = (-3.9 \pm 3.5 \pm 1.9) \times 10^{-3}$ in agreement with SM.

Flavour-changing neutral current

- CKM structure in SM allows only the charged interactions to change flavour.
- One can escape the CKM structure and produce $b \to s$ and $b \to d$ only at loop level.
  - This kind of process are suppressed by the GIM in SM $\to$ Rare decays.
- LHCb already sees a 3.7 σ deviation in the angular observables in $B^0 \to K^* \mu^- \mu^+$. See my talk: LINK.
- Here we present CP observables in $b \to s\gamma$ and $b \to s\ell\ell$ decays.
- SM prediction ~ 0

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CP asymmetries in B $\to X_s\gamma$

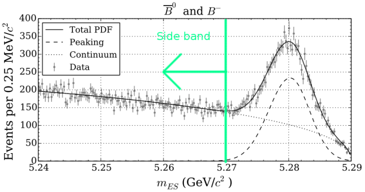
- Fully inclusive approach impossible.
- Instead use semi-inclusive (sum of exclusive modes).
- 16 modes used (marked with $*$)
- Additional requirements:

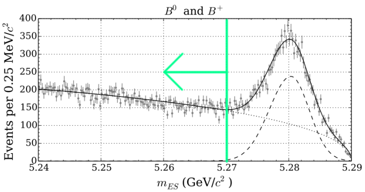
- PRD 90, 092001 (2014)
- Requirements:
  - $m(X_s) \in (0.6, 2.0)$ GeV
    - Indirect cut on $E_\gamma > 2.3$ GeV
  - $|\Delta E| < 0.15$ GeV
  - MVA based approach to get ride of $q\bar{q}$ background.

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

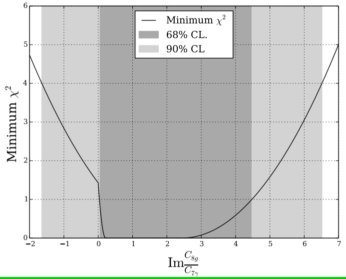
Asymmetry extraction

- Asymmetry for fitted yields needs to be corrected as in previous analysis detector asymmetries.
- Asymmetry extracted from side-bands.
  - (-1.4 ± 0.7) %.





- Results:
  - $A_{CP}(B^+ \to X_s^+\gamma) = (4.23 \pm 2.93 \pm 0.95)\%$
  - $A_{CP}(B^0 \to X_s^0\gamma) = (-0.74 \pm 2.57 \pm 1.10)\%$
  - Average:
  - $A_{CP} = (1.7 \pm 1.9 \pm 1.0)$ %
  - SM: $A_{CP} \sim 0 \leftrightarrow Im(C_8) \sim 0$



CP asymmetries in B $\rightarrow X_s \ell\ell$

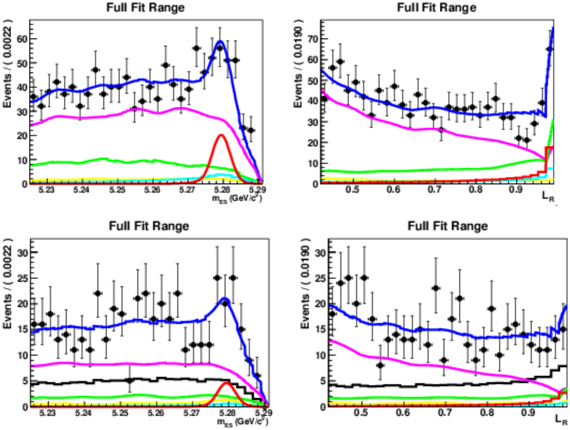
- Very important channel for NP searches.
- Significant deviation found by LHCb.
- CP observables are very clean predictions in SM and almost QCD free.
- Similar "semi-inclusive" modes:

$$X_s = \{K^+,\ K^+\pi^0,\ K^+\pi^-,\ K^+\pi^-\pi^0,\ K^+\pi^-\pi^+,\ K_s,\ K_s\pi^+,\ K_s\pi^+\pi^0,\ K_s\pi^+\pi^-\}$$

- Look for two leptons flavours: $\ell\ell = \{ee, \mu\mu\}$
- Additional requirements:
  - Require: $m(X_s) < 1.8$ GeV
  - $\Delta E \in [-0.1(-0.05), 0.05]$ GeV for $\ell\ell = ee$ $(\mu\mu)$

Differential branching fraction

- PRL 112 (2014) 211802
- J/ψ, $(\psi(2S))$ veto: 6.8 – 10.1 (12.9 – 14.2) GeV
- Suppress $q\bar{q}$ background with a BDT.
- Perform a simultaneous fit to m_{ES} and $L_R = \dfrac{\mathcal{P}_S}{\mathcal{P}_S + \mathcal{P}_B}$



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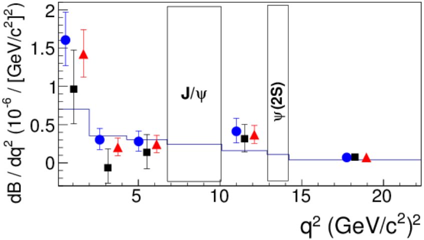
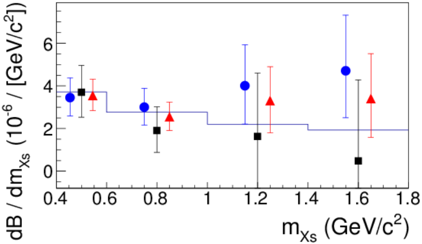
CP & BR asymmetries results

q^2 [GeV^2]	A_{CP}
$1.0 < q^2 < 6.0$	$-0.06 \pm 0.22 \pm 0.01$
$0.1 < q^2 < 2.0$	$-0.13 \pm 0.18 \pm 0.01$
$2.0 < q^2 < 4.3$	$0.42\ ^{+0.50}_{-0.42} \pm 0.01$
$4.3 < q^2 < 6.8$	$-0.45^{+0.44}_{-0.57} \pm 0.01$
$10.1 < q^2 < 14.2$	$0.19\ ^{+0.18}_{-0.17} \pm 0.01$

- electrons, muons, combined





- Measured branching fractions($\times 10^{-6}$) :

$$\mathcal{B}(B \to X_s e^- e^+) = 7.69^{+0.82}_{-0.77}{}^{+0.50}_{-0.33} \pm 0.50$$

$$\mathcal{B}(B \to X_s e^- e^+) = 4.41^{+1.31}_{-1.17}{}^{+0.57}_{-0.42} \pm 0.27$$

- Combined:

$$\mathcal{B}(B \to X_s \ell^- \ell^+) = 6.73^{+0.70}_{-0.64}{}^{+0.34}_{-0.25} \pm 0.50$$

- In agreement with SM.

Conclusions

1. B-factories still producing new results.
2. Presented new measurements of CP violation in neutral B meson system using inclusive dileptons events.
3. BaBar continues to chase FCNC with measurement of CP asymmetries in: $b \to s\gamma$ and $b \to s\ell\ell$
4. FCNC statistically limited: need future experiments.
5. All measurements consistent (for now?) with SM.

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