Time-dependent *CP* violation measurements in B decays from the Belle experiment

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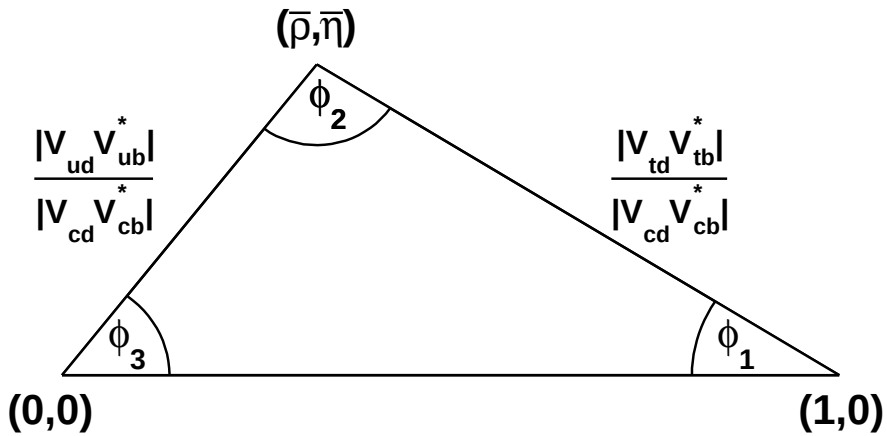
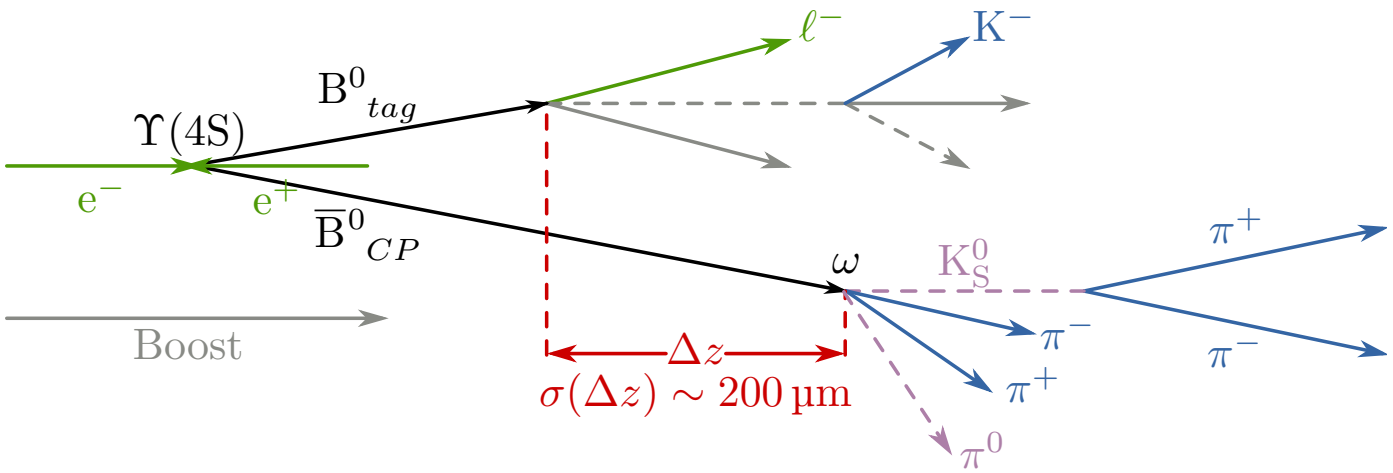
Outline



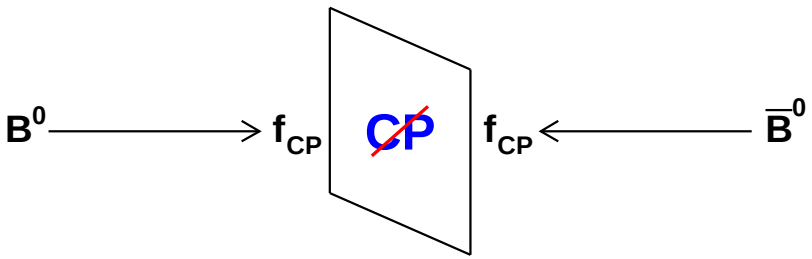
Types of *CP* Violation

Two types of *CP* violation can be measured from a *CP* final state of the B

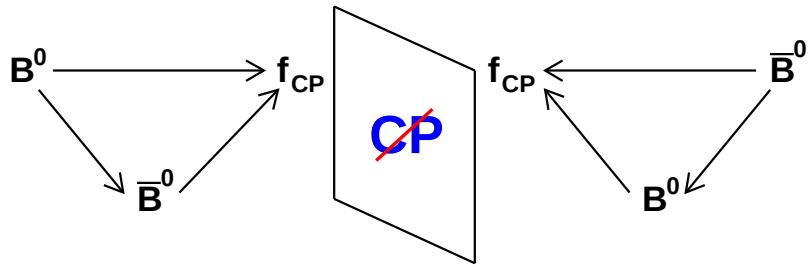
$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left[1 + q\left(\mathcal{A}_{CP} \cos \Delta m_d \Delta t + \mathcal{S}_{CP} \sin \Delta m_d \Delta t\right)\right]$$



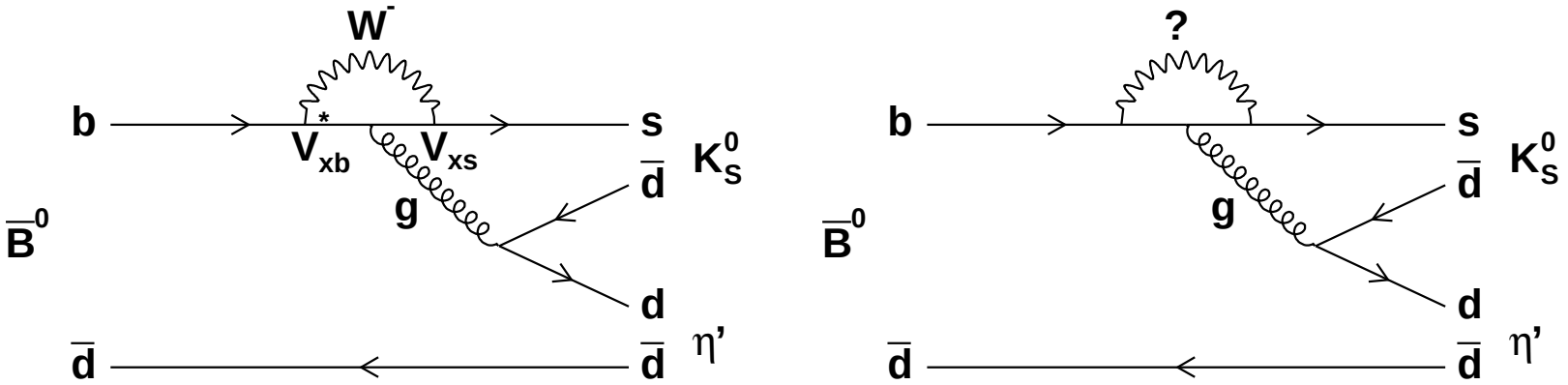
Direct *CP* violation $\mathcal{A}_{CP}$



Mixing-induced *CP* violation $\mathcal{S}_{CP}$

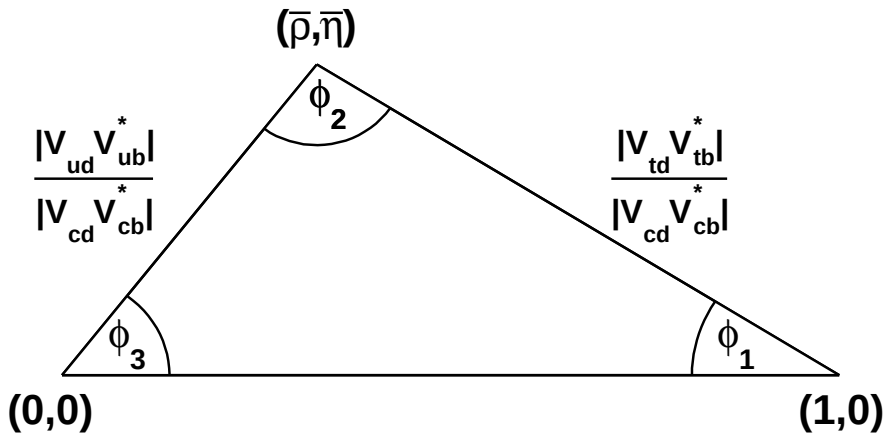


Measurement of ϕ_1: $b \to s q \bar{q}$



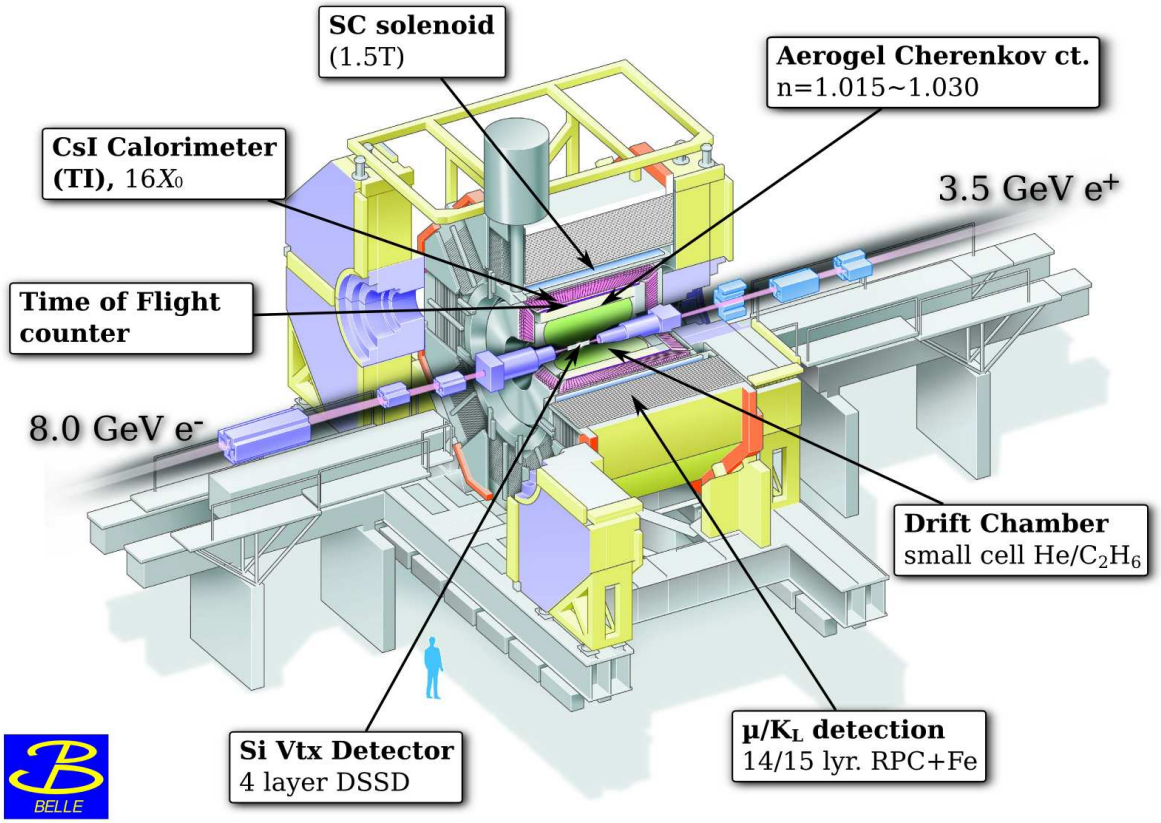
- Main contribution from loop-processes, tree contributions CKM suppressed
- $\mathcal{S}_{CP} = \sin 2\phi_1$, same as $b \to c\bar{c}s$
- Taking into account pollution from a tree process, $\mathcal{S}_{CP} = -f \sin 2\phi_1^{eff}$
- Penguin amplitudes highly sensitive to new physics
- Could be affected by a heavy unknown particle in the loop that can distort the measured $\sin 2\phi_1$ and branching fractions
  $\Rightarrow$ Deviations from the SM predictions could be a hint at new physics

Outline



$B^0 \to \eta' K^0$ event reconstruction

- SM prediction: $\Delta S_{\eta' K^0} = S_{\eta' K^0} - \sin 2\phi_1 \approx [-0.05; 0.09]$
- $B^0 \to \eta' K^0$ consists of two *CP* final states: $f = 1$ $(\eta' K^0_L)$ and $f = -1$ $(\eta' K^0_S)$



- K^0_S
  $\to \pi^+\pi^-$ and $\pi^0\pi^0$
- K^0_L
  ECL and/or KLM clusters without associated charged tracks
- η'
  $\to \rho^0\gamma$
  $\to \eta(\gamma\gamma)\pi^+\pi^-$
  $\to \eta(3\pi)\pi^+\pi^-$

Measurement of TCPV in $B^0 \to \eta' K^0$

- Main background $q\bar{q}$, further contribution from $b \to u, d, s, c$
- Suppression of $q\bar{q}$ BG with a likelihood ratio $\mathcal{R}_{s/b} = \mathcal{L}_{sig}/(\mathcal{L}_{sig} + \mathcal{L}_{bkg})$
- $\mathcal{L}$ contains a Fisher discriminant built from event-shape variables

Fit observables for signal yield extraction from full Belle data set

$B^0 \to \eta' K^0_S$

$$5.23\,\mathrm{GeV}/c^2 \leq M_{\mathrm{bc}}$$
$$-0.2\,\mathrm{GeV} \leq \Delta E \leq 0.2\,\mathrm{GeV}$$
$$0 \leq \mathcal{R}_{s/b} \leq 1$$

$$M_{bc} = \sqrt{E^2_{beam} - p^2_B}$$
$$\Delta E = E_B - E_{beam}$$

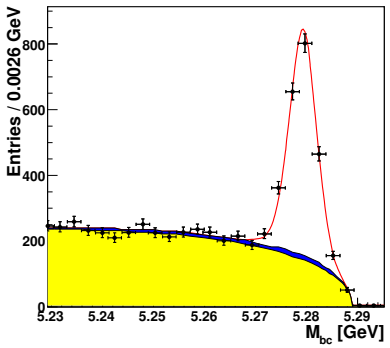
$B^0 \to \eta' K^0_L$

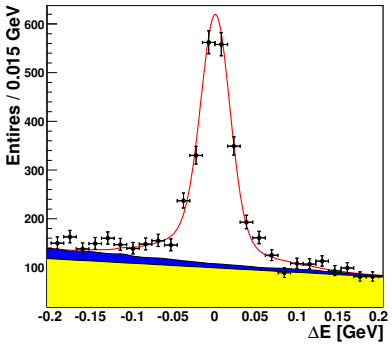
$$0\,\mathrm{GeV}/c \leq p^*_B \leq 2\,\mathrm{GeV}/c$$
$$0.5 \leq \mathcal{R}_{s/b} \leq 1$$

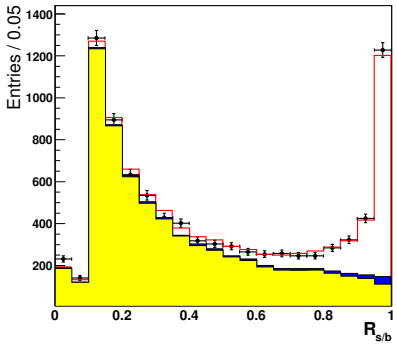
p^*_B: B momentum calculated assuming $\Delta E = 0$ and nominal $m_{K^0_L}$

Measurement of TCPV in $B^0 \to \eta' K^0$

$B^0 \to \eta' K^0_S$

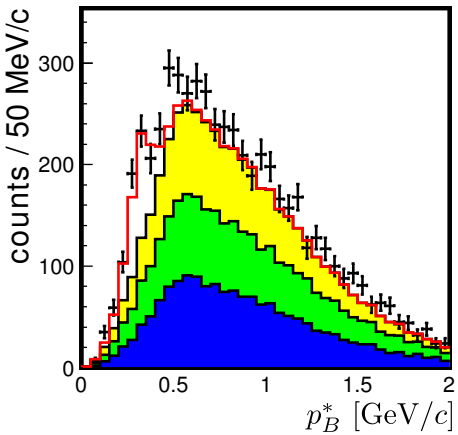


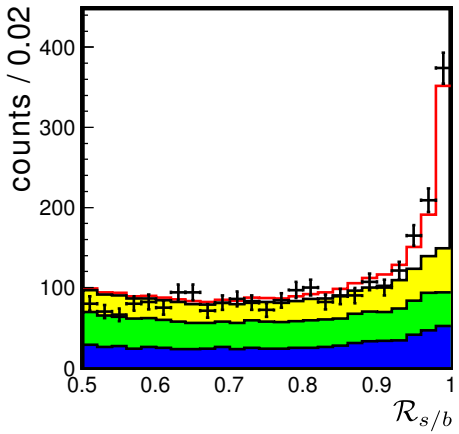




— total PDF
b → u, d, s, c BG
$q\bar{q}$ BG

$B^0 \to \eta' K^0_L$

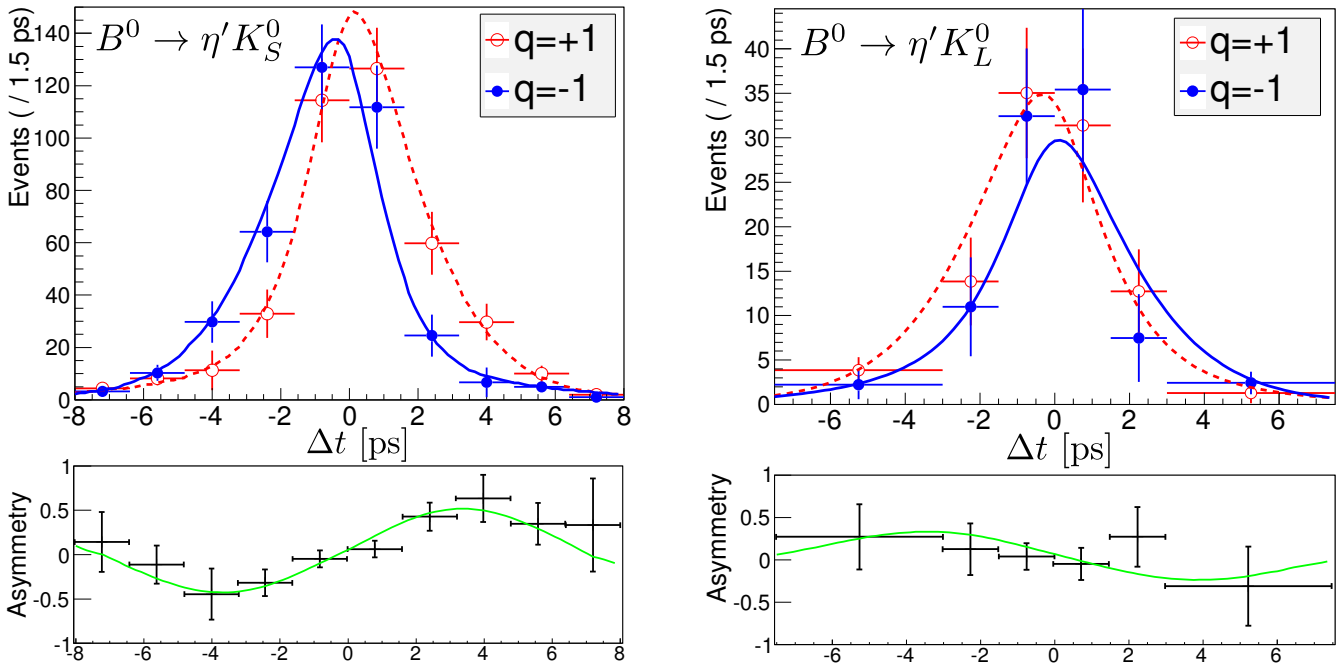




— total PDF
comb. BG with fake η'
comb. BG with fake K^0_L
comb. BG with real η' and K^0_L

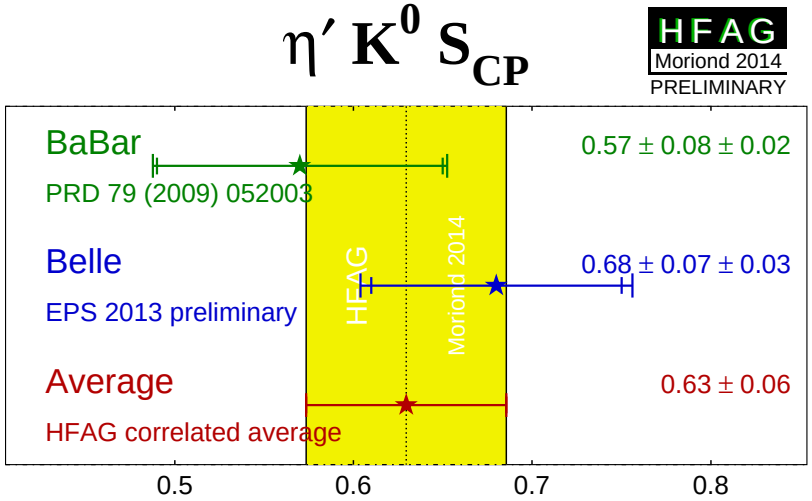
Signal yield: 3541 ± 91 events

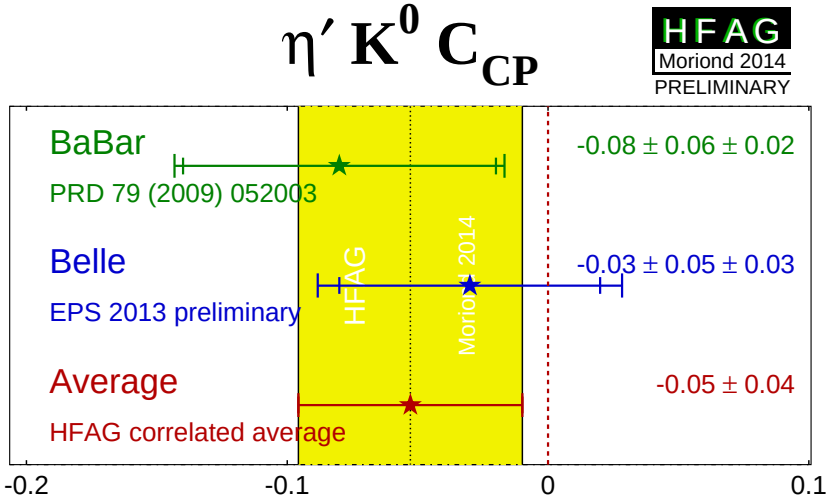
Measurement of TCPV in $B^0 \to \eta' K^0$



Decay mode	$-\xi_f \mathcal{S}_f$	$\mathcal{A}_f$
$\eta' K^0_S$	$+0.71 \pm 0.07$	$+0.02 \pm 0.05$
$\eta' K^0_L$	$+0.46 \pm 0.21$	$+0.09 \pm 0.14$
$\eta' K^0$	$+0.68 \pm 0.07 \pm 0.03$	$+0.03 \pm 0.05 \pm 0.04$

Measurement of TCPV in $B^0 \to \eta' K^0$



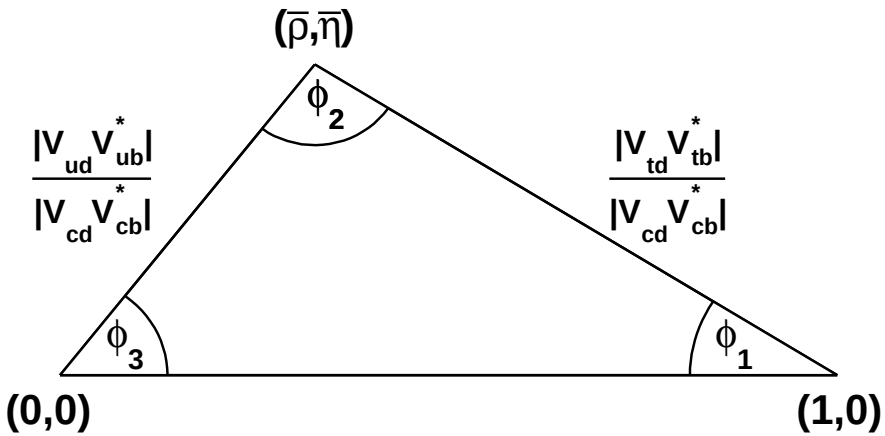


- Results consistent with previous Belle measurement

$$\mathcal{A}_{CP} = 0.01 \pm 0.07(\text{stat.}) \pm 0.05(\text{syst.})$$
$$\mathcal{S}_{CP} = 0.64 \pm 0.10(\text{stat.}) \pm 0.04(\text{syst.})$$

- World's most precise measurement to date of $B^0 \to \eta' K^0$ *CP* parameters
- $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP}$ values consistent with SM predictions

Outline

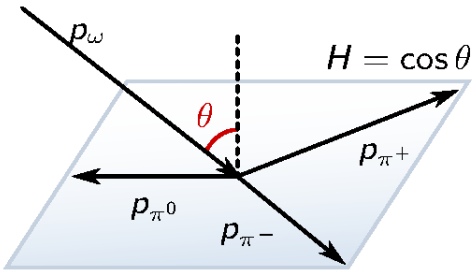


$B \to \omega K$ measurement

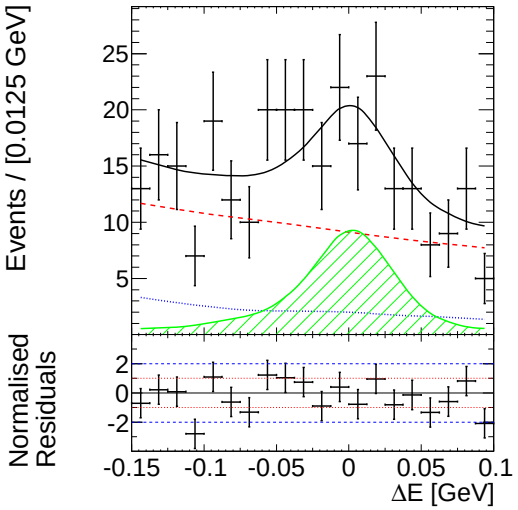
- SM prediction: $\Delta S_{\omega K^0_S} = S_{\omega K^0_S} - \sin 2\phi_1 \approx [0.1; 0.2]$
- $B^0 \to \omega K^0_S$ is a *CP* final state with $f = -1$
- Main BG contribution from $q\bar{q}$ events

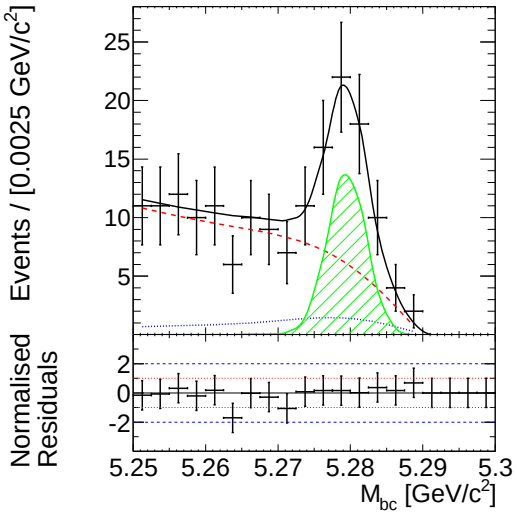
Extraction of $\mathcal{B}(\omega K^0)$, $\mathcal{B}(\omega K^+)$, $\mathcal{A}_{\omega K^0_S}$, $\mathcal{S}_{\omega K^0_S}$, $\mathcal{A}_{\omega K^+}$ from the full Belle data set.
Simultaneous extended 7D ML fit to

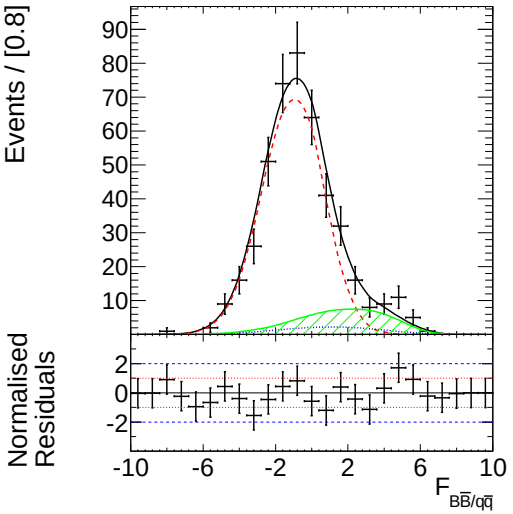
- ΔE
- M_{bc}
- $\mathcal{F}_{B\bar{B}/q\bar{q}}$
- $m(3\pi)$: mass of ω candidates
- $\mathcal{H}(3\pi)$: helicity of ω candidates
- Δt, q

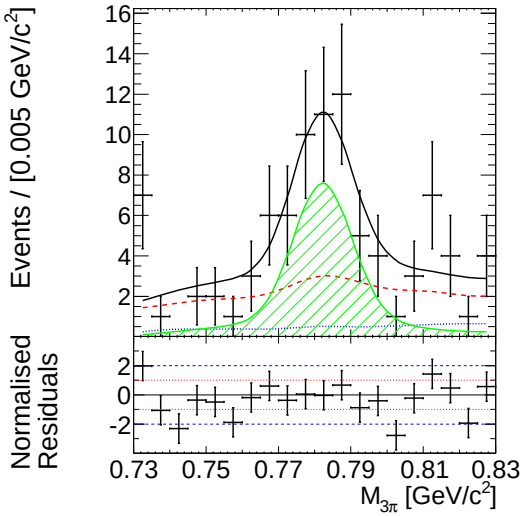


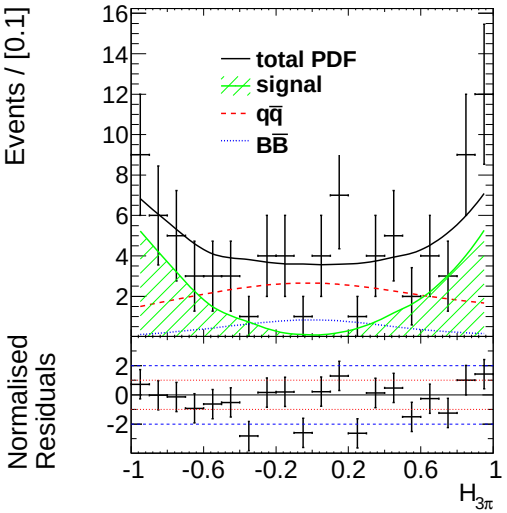
$B^0 \to \omega K^0_S$ results











— total PDF

- - $q\bar{q}$ BG

. . . $B\bar{B}$ BG

/// signal

$B \to \omega K$ results

Black font: previous measurements
Blue font: Full Belle data set of 772×10^6 $B\overline{B}$ pairs

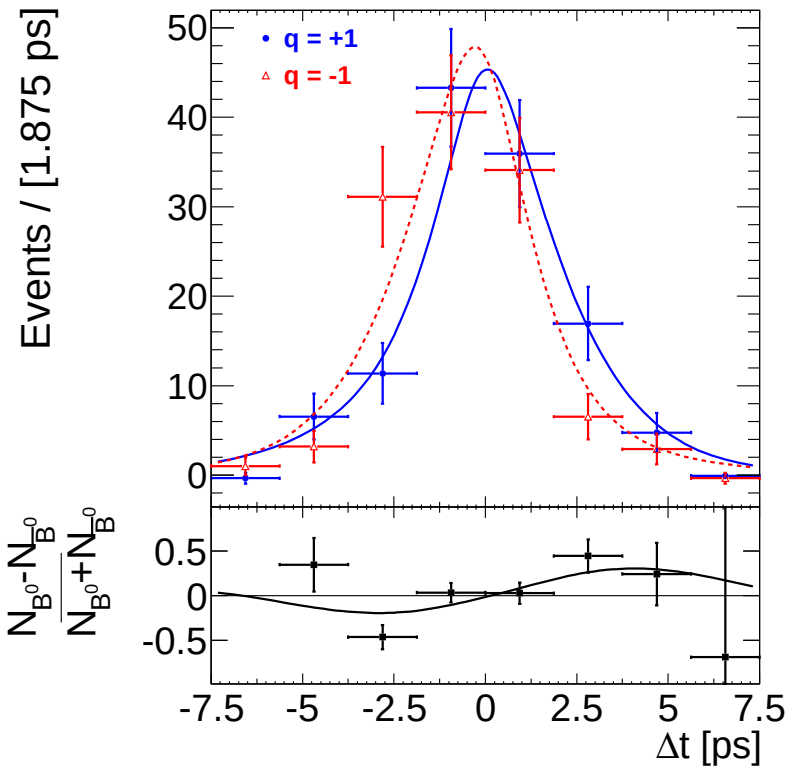
	$B\overline{B}$-pairs	$\mathcal{BR}(B^0 \to \omega K^0)$	$\mathcal{A}_{CP}$	$\mathcal{S}_{CP}$
Belle	388×10^6	$(4.4^{+0.8}_{-0.7} \pm 0.4) \times 10^{-6}$	-	-
Belle	535×10^6	-	$-0.09 \pm 0.29 \pm 0.06$	$+0.11 \pm 0.46 \pm 0.07$
BaBar	467×10^6	$(5.4 \pm 0.8 \pm 0.3) \times 10^{-6}$	$+0.52^{+0.22}_{-0.20} \pm 0.03$	$+0.55^{+0.26}_{-0.29} \pm 0.02$
Belle	772×10^6	$(4.5 \pm 0.4 \pm 0.3) \times 10^{-6}$	$-0.36 \pm 0.19 \pm 0.05$	$+0.91 \pm 0.32 \pm 0.05$

	$B\overline{B}$-pairs	$\mathcal{BR}(B^+ \to \omega K^+)$	$\mathcal{A}_{CP}$
Belle	388×10^6	$(8.1 \pm 0.6 \pm 0.6) \times 10^{-6}$	$+0.05^{+0.08}_{-0.07} \pm 0.01$
BaBar	383×10^6	$(6.3 \pm 0.5 \pm 0.3) \times 10^{-6}$	$-0.01 \pm 0.07 \pm 0.01$
Belle	772×10^6	$(6.8 \pm 0.4 \pm 0.4) \times 10^{-6}$	$-0.03 \pm 0.04 \pm 0.01$

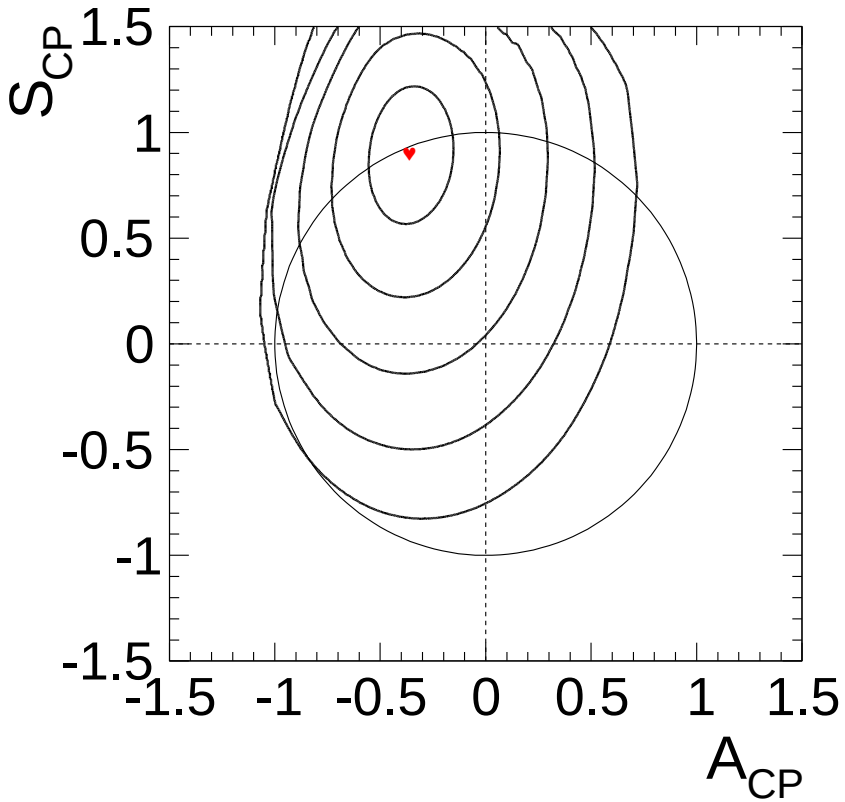
Paper accepted by PRD, to be published in the July '14 issue; arXiv 1311.6666

Measurement of ϕ_1: $B^0 \to \omega K^0_S$

First evidence of *CP* violation in $B^0 \to \omega K^0_S$

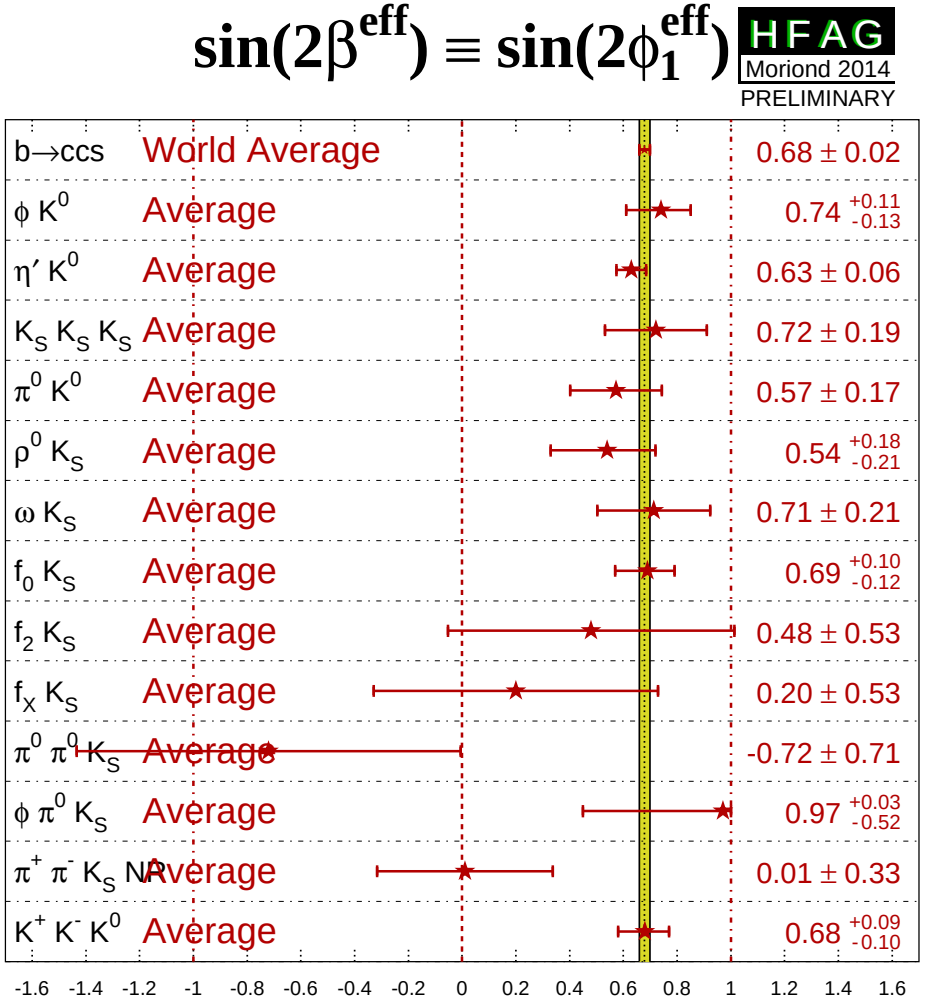


Clear asymmetry can be seen in the difference between the B^0 and $\overline{B}^0$ distributions



CP conservation $(\mathcal{A}_{CP}, \mathcal{S}_{CP}) = (0, 0)$ ruled out by 3.1 standard deviations

Measurement of ϕ_1: $b \to s\bar{q}q$



Belle final results

$$S_{\eta' K^0} = +0.68 \pm 0.07 \pm 0.03$$

$$S_{\omega K^0_S} = +0.91 \pm 0.32 \pm 0.05$$

Naïve $b \to s\bar{q}q$ average 0.655 ± 0.032

Conclusion

- $b \to sq\bar{q}$ decays sensitive to ϕ_1, measured value could be affected by new physics
- $B^0 \to \eta' K^0$ *CP* parameters results are world's most precise measurement, consistent with previous measurements
- $B \to \omega K$ measurements of branching fractions and *CP* parameters mostly consistent with previous results, four out of five parameters world's most precise results
- $b \to sq\bar{q}$ results consistent with ϕ_1 from $b \to c\bar{c}s$ transitions, more precision needed

Thank you for your attention

BACK UP

Systematic uncertainties $B^0 \to \eta' K^0$

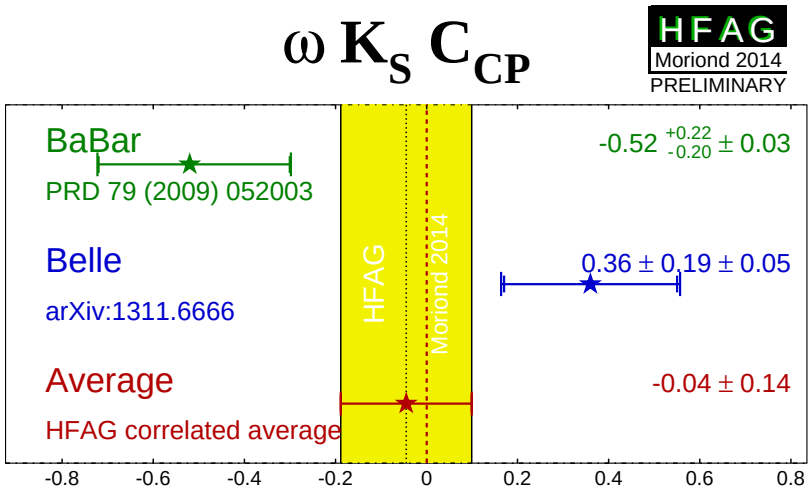
Source	$\mathcal{S}_{\eta' K^0}$	$\mathcal{A}_{\eta' K^0}$
Vertexing	± 0.014	± 0.033
Δt resolution	± 0.025	± 0.006
$\eta' K^0_S$ Signal fraction	± 0.013	± 0.006
$\eta' K^0_L$ Signal fraction	± 0.005	± 0.004
Background Δt PDF	± 0.001	< 0.001
Physics parameters	± 0.001	< 0.001
Possible fit bias	± 0.001	± 0.001
Flavor tagging	± 0.003	± 0.003
Tag-side interference	± 0.001	± 0.020
Total	± 0.032	± 0.040

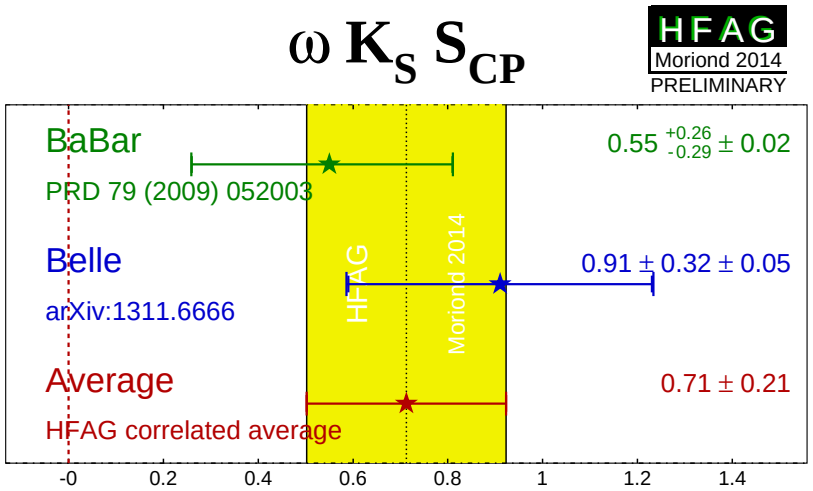
Measurement of TCPV in $B^0 \to \eta' K^0$

Fit performed in each tagging-quality bin and for each decay mode separately

		signal region		$+\mathcal{R}_{s/b} > 0.$
K^0 mode	η' mode	N_{sig}	purity	purity
$K^0_S \to \pi^+\pi^-$	$\rho^0\gamma$	1410.5 ± 48.5	0.19	0.59
	$\eta(\gamma\gamma)\pi^+\pi^-$	648.3 ± 27.9	0.49	0.89
	$\eta(3\pi)\pi^+\pi^-$	174.3 ± 13.5	0.65	0.94
$K^0_S \to \pi^0\pi^0$	$\rho^0\gamma$	162.2 ± 21.4	0.04	0.13
	$\eta(\gamma\gamma)\pi^+\pi^-$	104.0 ± 14.2	0.16	0.65
K_L	$\eta(\gamma\gamma)\pi^+\pi^-$	829.2 ± 54.0	0.30	
	$\eta(3\pi)\pi^+\pi^-$	612.5 ± 36.1	0.19	
Total		3941.0 ± 90.5		

Higher signal yield than previous analysis (+ 20%) due to improved tracking and K^0_S selection


ω K_S C_CP
HFAG
Moriond 2014
PRELIMINARY
BaBar
PRD 79 (2009) 052003
-0.52 +0.22 -0.20 ± 0.03
Belle
arXiv:1311.6666
0.36 ± 0.19 ± 0.05
Average
HFAG correlated average
-0.04 ± 0.14
HFAG
Moriond 2014
-0.8 -0.6 -0.4 -0.2 0 0.2 0.4 0.6 0.8


ω K_S S_CP
HFAG
Moriond 2014
PRELIMINARY
BaBar
PRD 79 (2009) 052003
0.55 +0.26 -0.29 ± 0.02
Belle
arXiv:1311.6666
0.91 ± 0.32 ± 0.05
Average
HFAG correlated average
0.71 ± 0.21
HFAG
Moriond 2014
-0 0.2 0.4 0.6 0.8 1 1.2 1.4

$B \to \omega K$ systematic uncertainties

Category	$\delta\mathcal{B}(\omega K^0_S)$ (%)	$\delta\mathcal{A}_{\omega K^0_S}$ (10^{-2})	$\delta\mathcal{S}_{\omega K^0_S}$ (10^{-2})	$\delta\mathcal{B}(\omega K^+)$ (%)	$\delta\mathcal{A}_{\omega K^+}$ (10^{-2})
$N_{B\overline{B}}$	1.4	N/A	N/A	1.4	N/A
π^0 reconstruction	4.0	N/A	N/A	4.0	N/A
K^0_S reconstruction	0.8	N/A	N/A	N/A	N/A
PID	1.8	N/A	N/A	2.8	N/A
Tracking	0.7	N/A	N/A	1.1	N/A
Vertex quality selection	0.9	0.3	0.5	0.9	N/A
Δt resolution function	0.6	2.6	4.4	0.8	0.7
Flavor-tagging	0.0	0.3	0.8	0.0	N/A
Misreconstruction	0.9	0.1	0.3	0.7	0.1
$B\overline{B}$ background yields	0.8	0.2	0.5	0.9	0.3
Parametric shape	1.8	0.5	1.5	1.0	0.5
Nonparametric shape	0.1	0.1	0.2	0.1	0.3
Fit bias	0.6	0.7	0.1	0.9	0.3
Background *CP* violation	N/A	1.5	1.4	N/A	0.1
Tag-side interference	N/A	3.2	0.2	N/A	N/A
Total	5.5	4.6	5.2	5.6	1.0

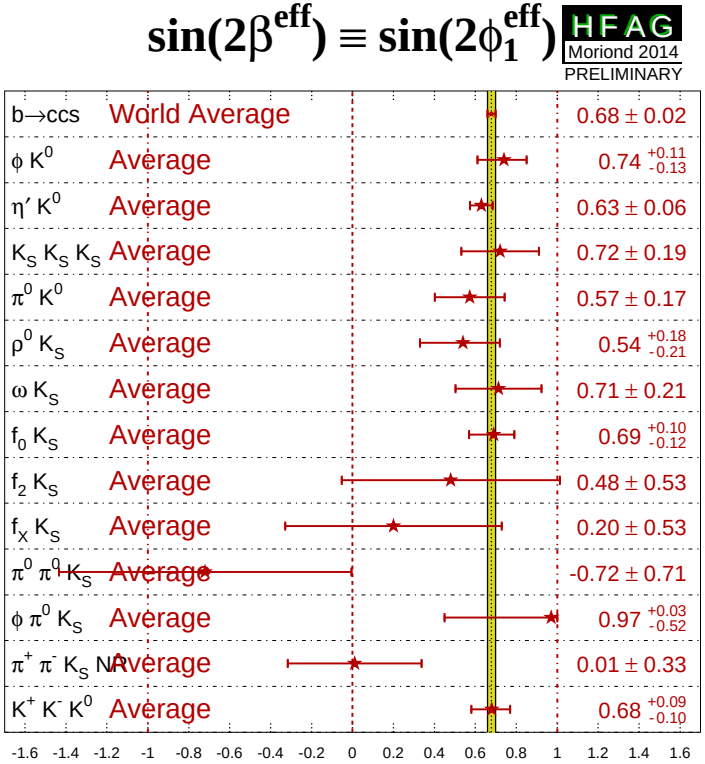
Measurement of ϕ_1: $b \to s q \bar{q}$

Theory

hep-ph/0707.1323, hep-ph/0702252

Mode	$\mathcal{S}_{CP} - \sin 2\phi_1$
$B^0 \to \phi K^0_S$	0.02 ± 0.01
$B^0 \to \eta' K^0_S$	0.01 ± 0.01
$B^0 \to K^0_S K^0_S K^0_S$	$0.02^{+0.02}_{-0.03}$
$B^0 \to K^0_S \pi^0$	$0.07^{+0.05}_{-0.04}$
$B^0 \to \rho^0 K^0_S$	$-0.08^{+0.08}_{-0.12}$
$B^0 \to \omega K^0_S$	0.13 ± 0.08
$B^0 \to K^0_S \pi^0 \pi^0$	$0.03^{+0.02}_{-0.03}$
$B^0 \to K^+ K^- K^0_S$	$0.03^{+0.02}_{-0.03}$

Experiment



Predicted in SM to have higher *CP* asymmetries than $b \to s q \bar{q}$

But most $b \to s q \bar{q}$ measurements at or below $b \to c \bar{c} s$ measurements

More experimental precision required