Measurements of $B^0 \to J/\psi\pi^0$ and other CPV modes at Belle

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on behalf of the Belle and Belle II Collaborations

Contents

- Branching fraction & CP asymmetries in $B^0 \to J/\Psi\pi^0$
- CP asymmetries in $B^0 \to K_S\pi^0\pi^0$
- Measurements of cos $(2\Phi_1)$ (BaBar + Belle combined)

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BELLE

BROOKHAVEN NATIONAL LABORATORY

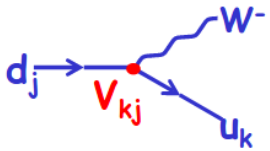
Introduction

CPV: due to **a complex phase** in the quark mixing matrix

CKM matrix

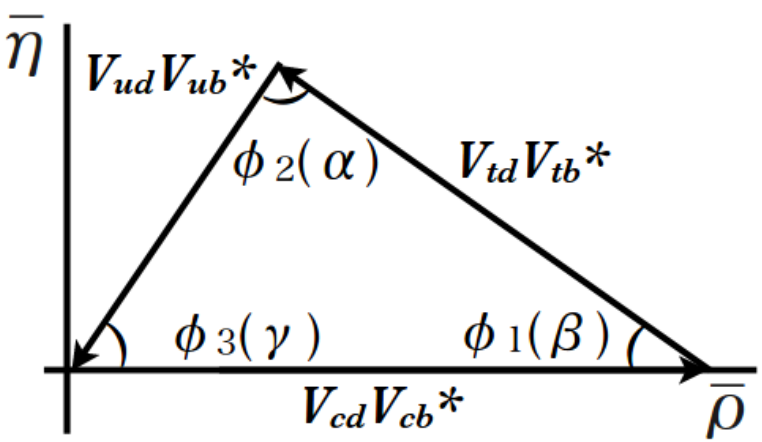
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM matrix connects quark mass eigenstates to weak interaction eigenstates and thus describes coupling strength of quarks to charged current weak interaction



Unitarity requires

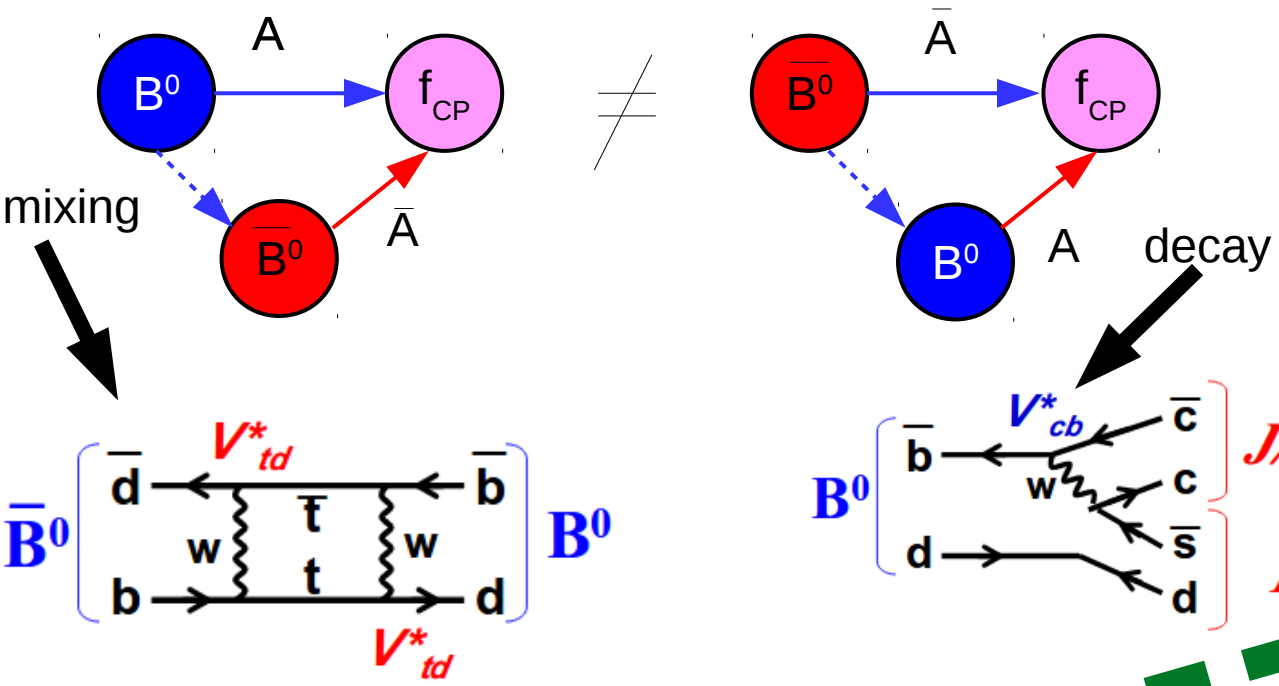
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



Wolfenstein representation

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

CPV in B decays



- CPV in decays
- CPV in mixing
- CPV in interference bet^n a decay with and without mixing

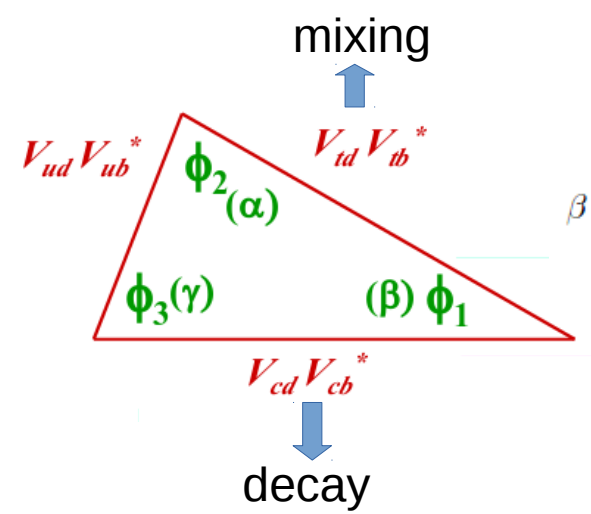
Time-dependent CP violation

$$A_{CP} \equiv \frac{\Gamma(\overline{B}^0 \to f_{CP}\,;\,\Delta t) - \Gamma(B^0 \to f_{CP}\,;\,\Delta t)}{\Gamma(\overline{B}^0 \to f_{CP}\,;\,\Delta t) + \Gamma(B^0 \to f_{CP}\,;\,\Delta t)}$$

$$= S\sin(\Delta m_d \Delta t) + A\cos(\Delta m_d \Delta t)$$

Mixing-induced CPV → Directly related to CKM angles

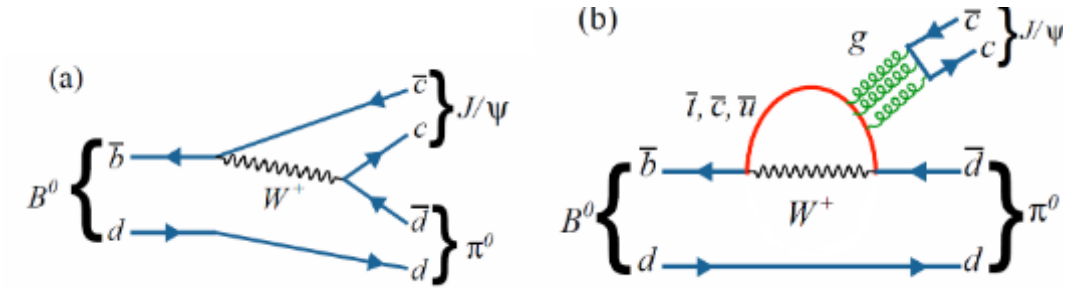
Direct CPV



$$\beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right]$$

[1] A. B. Carter and A. I. Sanda, PRD 23, 1567 (1981)
[2] I. I. Bigi and A. I. Sanda, NPB 193, 85 (1981)

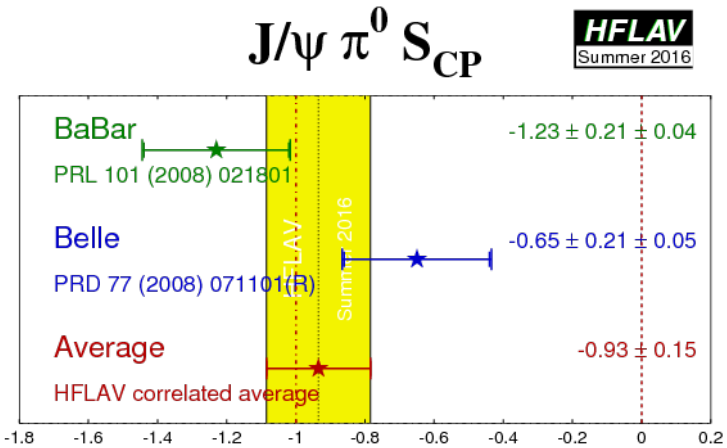
$B^0 \rightarrow J/\Psi\pi^0$: analysis motivation

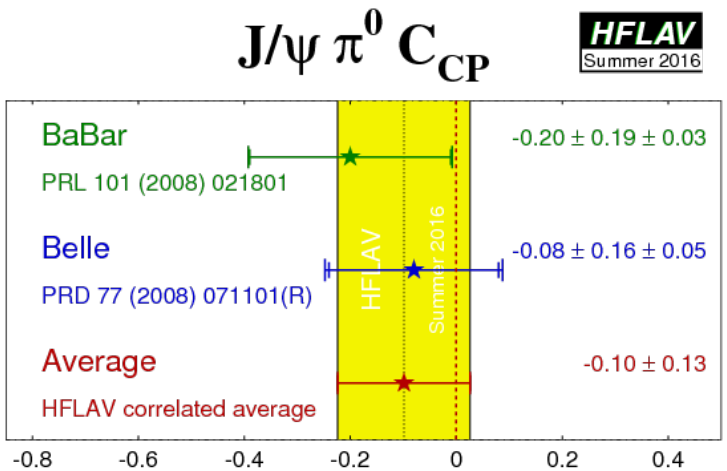


- These decays are sensitive to the *CP* violating angle $\Phi_1(\beta)$ of the unitarity triangle
- In the absence of the penguin amplitude, the direct *CP* asymmetry $A = 0$ and the mixing-induced *CP* asymmetry $S = -\sin(2\Phi_1)$
- Penguin and/or any new physics (NP) process will shift *A* and *S* from these values. Thus, experimental measurement of these parameters provide a way to search for NP.
- The values of *A* and *S* in this decay are useful to constrain the penguin pollution in the golden mode $B^0 \rightarrow J/\psi\, K_S$ decays [1,2,3,4,5]

1) M. Ciuchini et al, PRL 95, 221804 (2005)
2) S. Faller et al, PRD 79, 014030 (2009)
3) M. Jung, PRD 86, 053008 (2012)
4) Z. Ligeti and D. Robinson, PRL 115, 251801 (2015)
5) P. Frings et al, PRL 115, 061802 (2015)

$B^0 \to J/\Psi\pi^0$: analysis motivation





- Previous measurements of mixing induced CP asymmetries from BaBar and Belle experiments are not in good agreement and BaBar result lies outside the physically allowed region (although the error is large)
- A more precise measurement can clarify this unsatisfactory situation
- Previous Belle measurement is based on 535M BB pairs.
- We expect improvement with final Belle data set, which corresponds to 772M BB pairs.

$B^0 \to J/\Psi\pi^0$: analysis motivation

$B^0 \to J/\psi(1S)\pi^0$ INSPIRE search

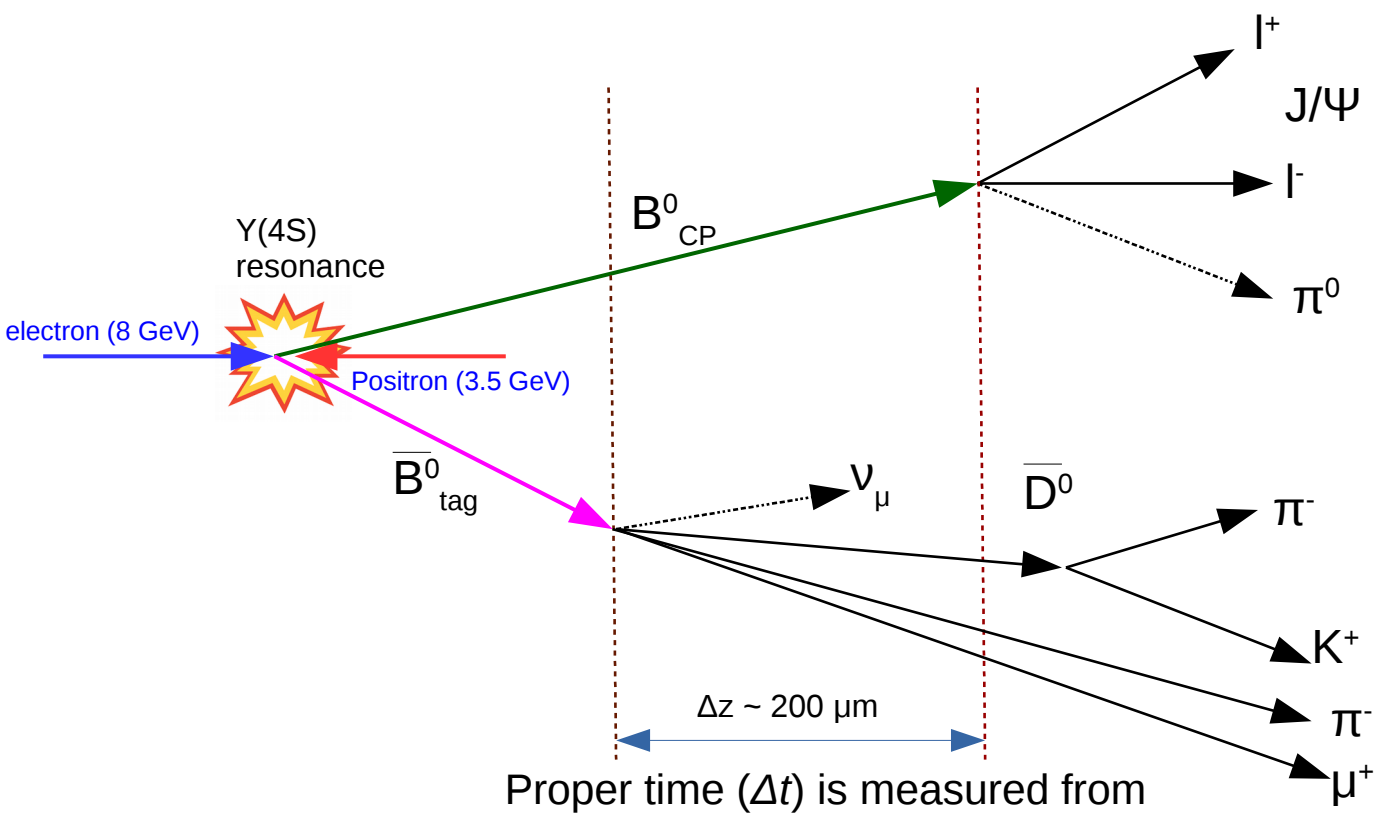
$\Gamma(B^0 \to J/\psi(1S)\pi^0)/\Gamma_{total}$ Γ_{193}/Γ

VALUE (10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
1.76 ± 0.16	**OUR AVERAGE** Error includes scale factor of 1.1.				
1.69 ±0.14 ±0.07		1 AUBERT	2008AU	BABR	$e^+ e^- \to \Upsilon(4S)$
2.3 ±0.5 ±0.2		1 ABE	2003B	BELL	$e^+ e^- \to \Upsilon(4S)$
$2.5 \pm^{1.1}_{0.9} \pm 0.2$		1 AVERY	2000	CLE2	$e^+ e^- \to \Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.94 ±0.22 ±0.17		1 AUBERT,B	2006B	BABR	Repl. by AUBERT 2008AU
2.0 ±0.6 ±0.2		1 AUBERT	2002	BABR	Repl. by AUBERT,B 2006B
< 32	90	2 ACCIARRI	1997C	L3	
< 5.8	90	BISHAI	1996	CLE2	Sup. by AVERY 2000
< 690	90	1 ALEXANDER	1995	CLE2	Sup. by BISHAI 1996

Previous Belle measurement of the branching fraction was only with 30/fb. With the final data set, we expect huge improvement

Reconstruction: $J/\psi \to \mu^+\mu^-$, e^+e^- and $\pi^0 \to$ 2 gamma
Background components are $B \to J/\psi K_S$, $B \to J/\psi K_L$, other $B \to J/\psi X$ and continuum

Vertex reconstruction & Flavor tagging



We fully reconstruct one *B* meson which decays to *CP* eigenstate $J/\Psi\pi^0$ for this case.

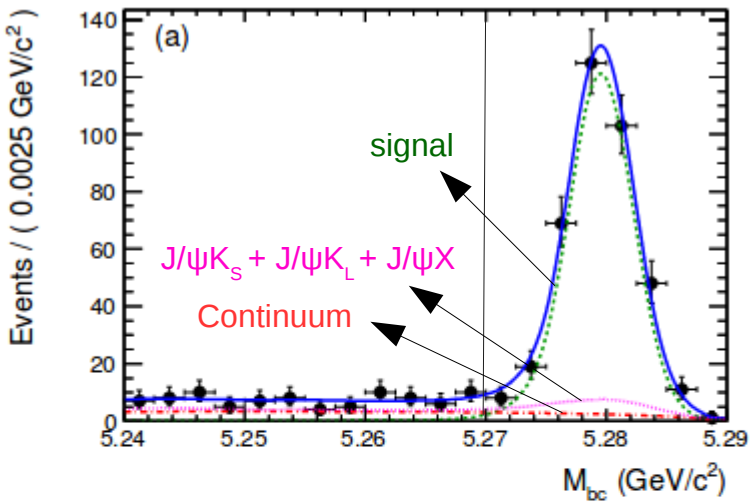
Since there are no other particles in the event beside the two *B* mesons, all tracks that are not associated to B_{CP} are used to reconstruct the B_{tag} vertex. [H. Tajima et al, NIM A 533, 370 (2004)]

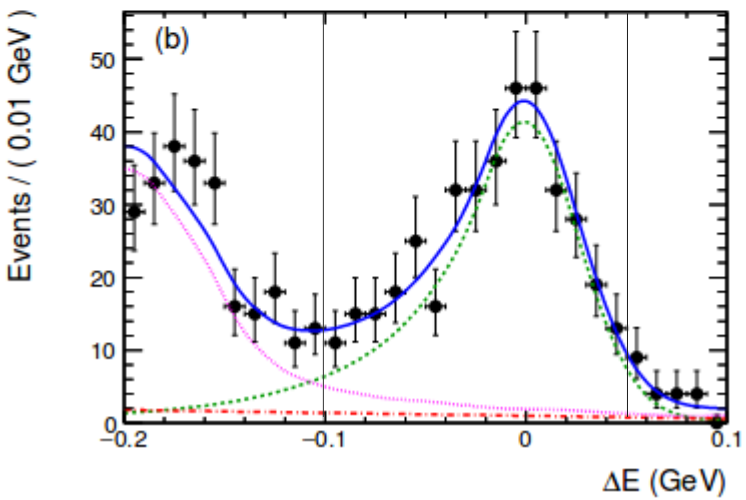
Proper time (Δt) is measured from decay-vertex difference Δz:
$\Delta t \approx \Delta z/\beta\gamma c$, $\beta\gamma = 0.425$ is the boost factor

Tag side determines the initial flavor. The effective tagging efficiency ~30%.[H. Kakuno et al, NIM A 533, 516 (2004)]

Event with poorly reconstructed vertices are rejected by applying cut on the vertex χ^2 and error on the vertex z-coordinate.

Branching fraction measurement





Signal = 330 ± 22
Continuum bkg = 16 ± 4

$$\mathcal{B}(B^0 \to J/\psi\pi^0) = \frac{Y_{\rm sig}}{\varepsilon \times N_{B\bar{B}} \times \mathcal{B}_{J/\psi} \times \mathcal{B}_{\pi^0}}$$

$$\mathcal{B}(B^0 \to J/\psi\pi^0) = (1.55 \pm 0.10\,^{+0.06}_{-0.07}) \times 10^{-5}$$

PRELIMINARY

TABLE I. Fractional systematic uncertainties for $\mathcal{B}(B^0 \to J/\psi\pi^0)$.

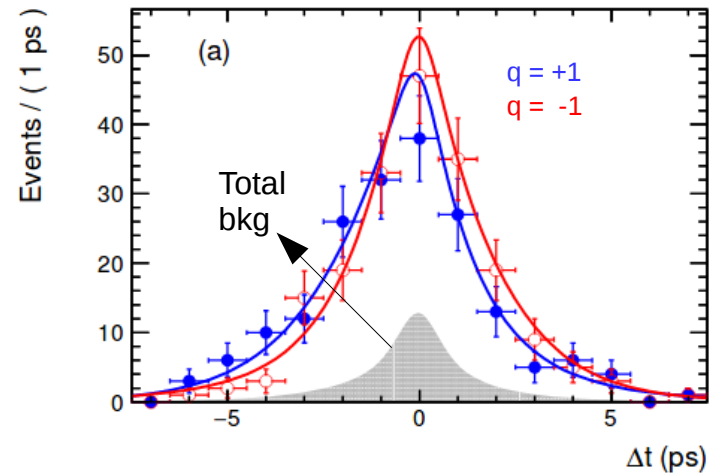
Source	Uncertainty (%)
PDF parametrization	0.1
π^0 reconstruction	1.5
Tracking	0.7
Lepton-ID selection	2.1
Incorrectly reconstructed signal events	1.8
$B \to J/\psi\,(K^0_S, K^0_L, X)$ background	$^{+1.8}_{-2.0}$
MC statistics	0.4
Secondary branching fractions	0.8
Number of $B\bar{B}$ pairs	1.4
Total	$^{+4.0}_{-4.2}$

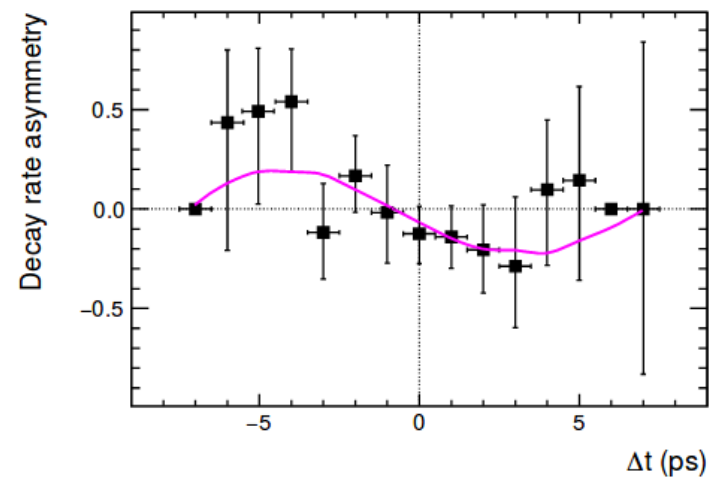
Our measurement is consistent with the WA and more precise than any previous measurement!

VALUE (10^{-5})	*CL%*	*DOCUMENT ID*		*TECN*
1.76 ± 0.16	**OUR AVERAGE**	Error includes scale factor of 1.1.		
1.69 ±0.14 ±0.07		1 AUBERT	2008AU	BABR
2.3 ±0.5 ±0.2		1 ABE	2003B	BELL
2.5 $^{+1.1}_{-0.9}$ ±0.2		1 AVERY	2000	CLE2

Measurements of S and A

$$\mathcal{P}_i(\Delta t) = (1-f_{\rm ol})\int d(\Delta t')\Big[R_{\rm sig}(\Delta t_i-\Delta t')\times \Big(f_{\rm sig}\mathcal{P}_{\rm sig}(\Delta t') + f_{J/\psi K^0_S}\mathcal{P}_{J/\psi K^0_S}(\Delta t') + f_{J/\psi K^0_L}\mathcal{P}_{J/\psi K^0_L}(\Delta t') + f_{J/\psi X}\mathcal{P}_{J/\psi X}(\Delta t')\Big) + f_{q\bar{q}}\mathcal{P}_{q\bar{q}}(\Delta t_i)\Big] + f_{\rm ol}\mathcal{P}_{\rm ol}(\Delta t_i)\,, \quad (3)$$





$$(Y_{\rm sig}^{(q=+1)} - Y_{\rm sig}^{(q=-1)})/(Y_{\rm sig}^{(q=+1)} + Y_{\rm sig}^{(q=-1)})$$

- For $B^0 \to J/\Psi K_S$ and $B^0 \to J/\Psi K_L$, the PDF is similar to signal PDF, but S and A are fixed to the results from [PRL 108, 171802 (2012)]
- For $B^0 \to J/\Psi X$ we also use the same PDF but with A = 0, S = 0 and B lifetime is replaced with effective lifetime. Effective lifetime is measured from MC (100x the data) and fixed in the fit to data.
- Sideband data is used to study qq background.
- Outlier component described by a board Gaussian with small fraction.
- The resolution function [H. Tajima et al, NIM A 533, 370 (2004)] is a convolution of four components: B_{CP} vertex resolution, B_{tag} vertex resolution, Shift of the B_{tag} vertex position due to secondary tracks from charmed particle decay, the kinematic approximation that the B mesons are at rest in the CM frame.

$$\mathcal{S} = -0.59 \pm 0.19 \pm 0.03$$
$$\mathcal{A} = -0.15 \pm 0.14\,^{+0.04}_{-0.03}\,,$$

PRELIMINARY

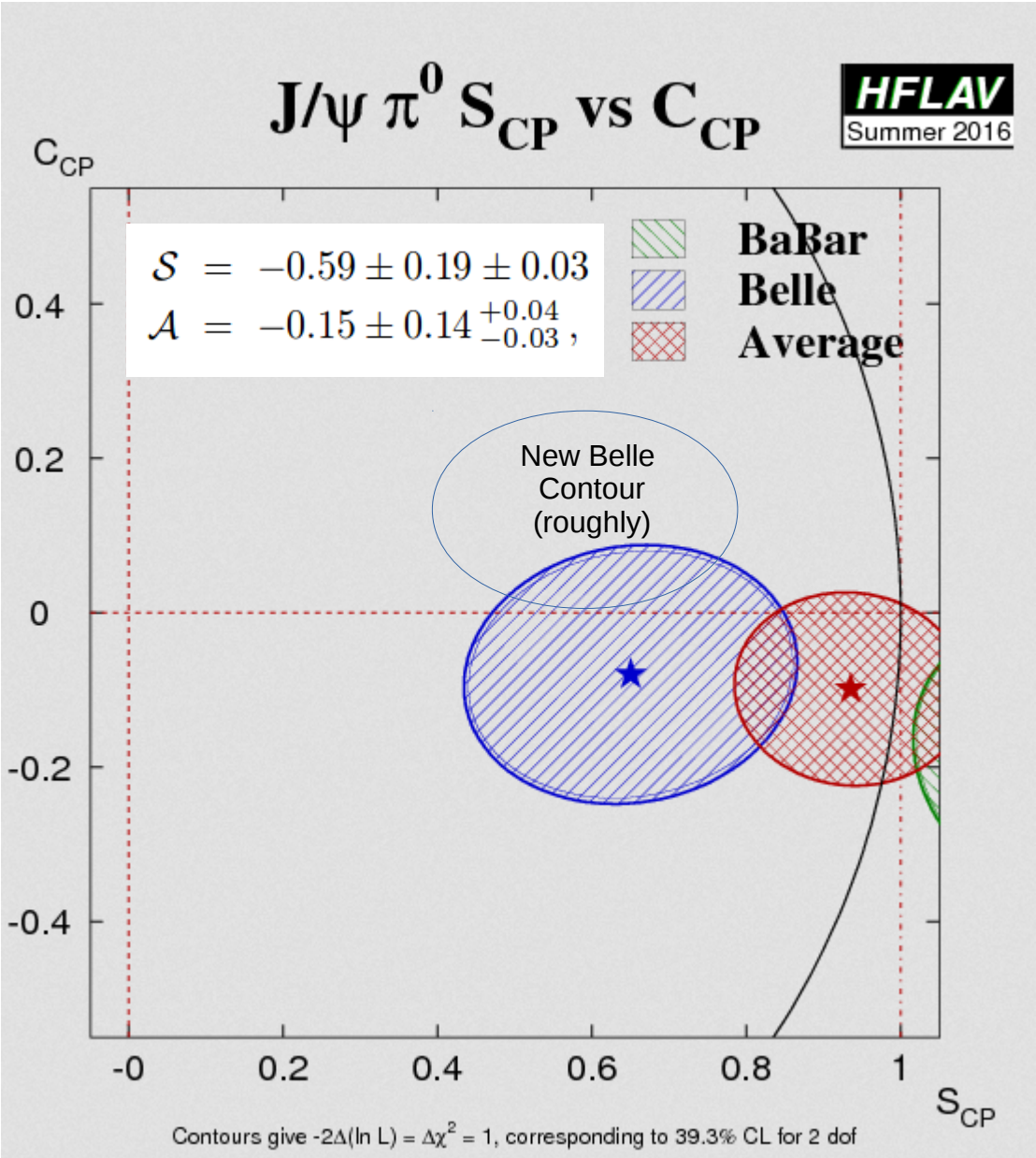
Manuscript to be submitted soon

Systematic uncertainties

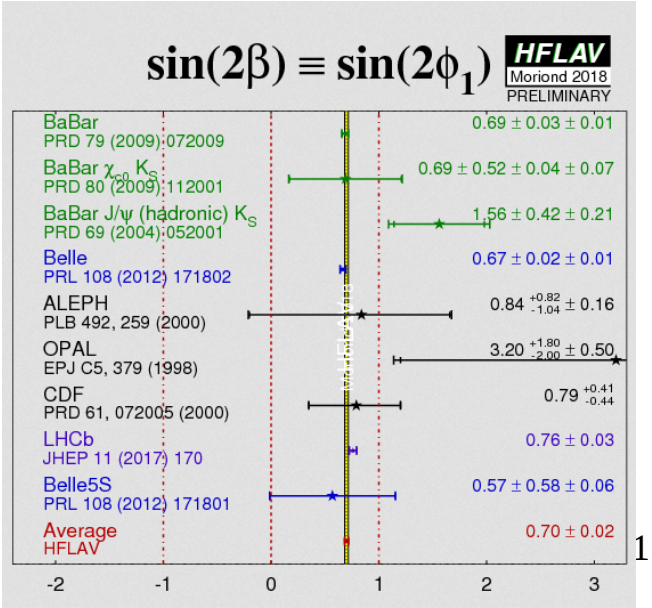
TABLE II. Systematic uncertainties for $\mathcal{S}$ and $\mathcal{A}$.

Source	$\mathcal{S}$ (%)	$\mathcal{A}$ (%)
Vertex reconstruction	$^{+2.36}_{-1.75}$	$^{+1.40}_{-2.22}$
Resolution function	$^{+1.43}_{-2.37}$	$^{+1.00}_{-0.91}$
Physics parameters	$^{+0.04}_{-0.03}$	± 0.04
Fit bias	± 0.68	± 0.27
Wrong tag fraction	$^{+0.41}_{-0.20}$	$^{+0.43}_{-0.17}$
$M_{\rm bc} - \Delta E$ Shape	$^{+0.52}_{-0.45}$	$^{+0.50}_{-0.48}$
Signal and background fraction	$^{+0.71}_{-0.62}$	$^{+0.49}_{-0.72}$
Background Δt shape	$^{+0.20}_{-0.12}$	± 0.10
Tag side interference	± 0.20	$^{+3.80}_{-0.00}$
Total	$^{+3.02}_{-3.14}$	$^{+4.26}_{-2.57}$

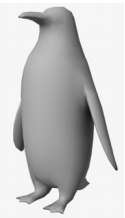
Measurements of S and A: discussions

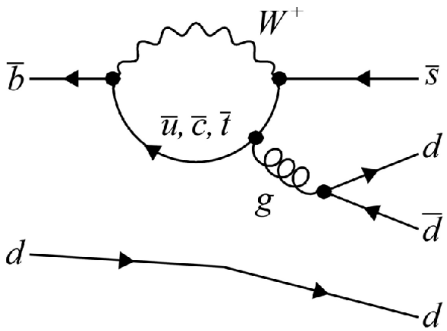


- Our measured CP asymmetries are consistent with and supersede our previous measurements.
- S differs from zero by 3.0 standard deviations
  - We also differ from BaBar by 3.2 standard deviations
- Our measured value is consistent with the measurements from b→ccs channels



Sin $(2\Phi_1)$ in $b \to s q\bar{q}$ transition ($B^0 \to K_S \pi^0\pi^0$)

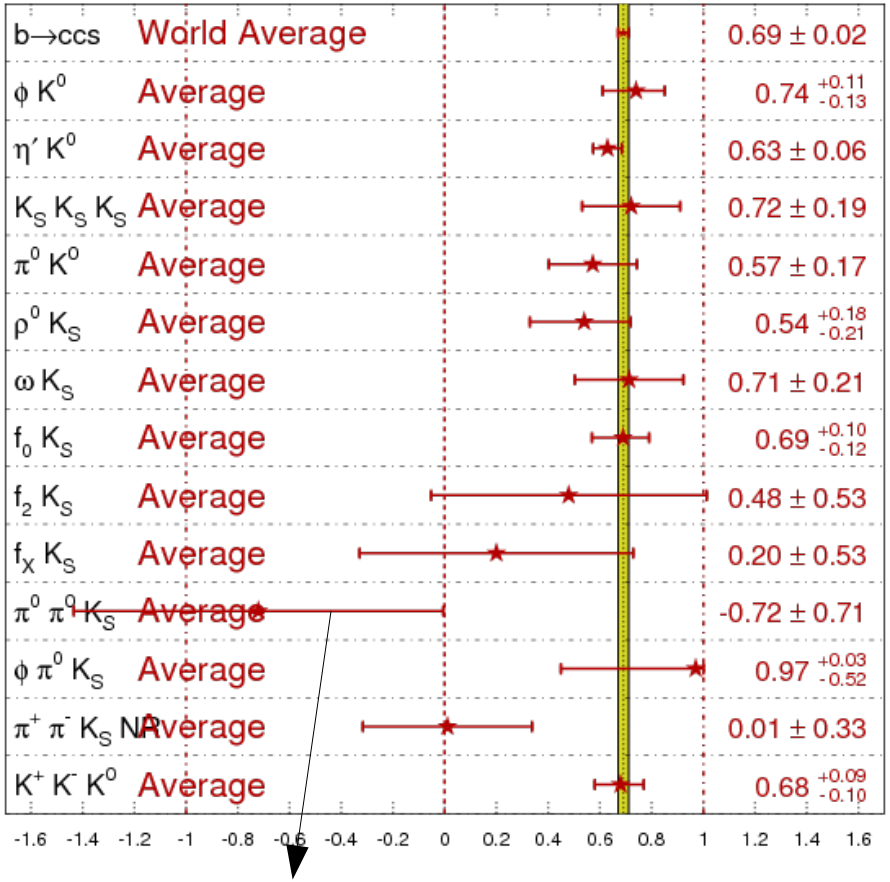




- Penguin loop is sensitive to the new physics contribution.
- Only few CP-even $b \to sqq$ modes are studied: φK_L, ηK_L, $K_S\pi^0\pi^0$

- Reconstruction: $K_S \to \pi^+\pi^-$, $\pi^0 \to 2$ gamma
- Background: continuum and BB
- Veto: $M_{\pi0\pi0} < 0.6$ GeV, 2.8 GeV $< M_{\pi0\pi0} <$ 3.6 GeV, 1.77 GeV $< M_{Ks\pi0} < 1.94$ GeV and $M_{Ks\pi0} > 4.8$ GeV
- Reconstruction of signal side vertex with flight direction of K_S with the constraint of interaction point

$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$ HFLAV Summer 2016



2.2 σ deviation from the $\sin(2\Phi_1)$ measured in $b \to$ css decays.
BaBar 227M BB PRD 76, 071101 (2007)

Sin ($2\Phi_1$) in $b \to s q\bar{q}$ transition

- Signal yield with vertex reconstruction 146.7 ± 23.6 (purity 11.4%)

PRELIMINARY

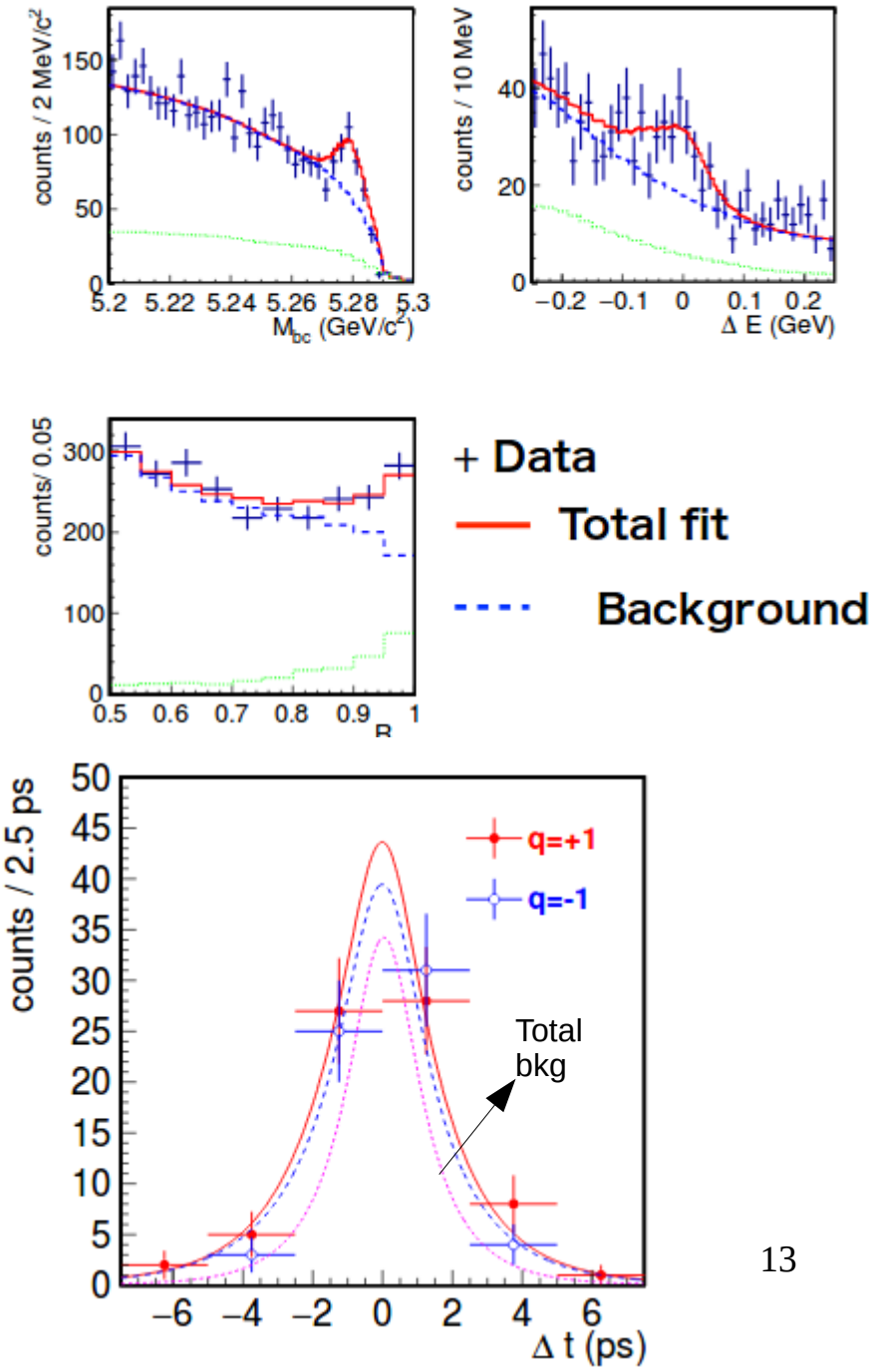
$$\sin 2\phi_1^{\rm eff} = 0.92^{+0.27}_{-0.31}\ (\text{stat.})\ ^{+0.10}_{-0.11}\ (\text{syst.})$$
$$\mathcal{A} = 0.28 \pm 0.21\ (\text{stat.})\ \pm 0.04\ (\text{syst.})$$

- The result of sin ($2\Phi_1$) is consistent with the value measured in $b \to$ ccs decays
- Statistical uncertainties are large

TABLE I. Systematic uncertainties

	$\Delta \sin 2\phi_1^{\rm eff}$	$\Delta\mathcal{A}$
Vertexing	±0.02	±0.01
Flavor tagging	±0.004	±0.003
Resolution function	±0.06	$^{+0.004}_{-0.003}$
Physics parameters	±0.002	< 0.001
Fit bias	±0.03	±0.02
Background fraction	±0.02	±0.02
Background Δt	±0.08	±0.02
Tag-side interference	±0.001	±0.008
Total	±0.11	±0.04

Manuscript to be submitted soon

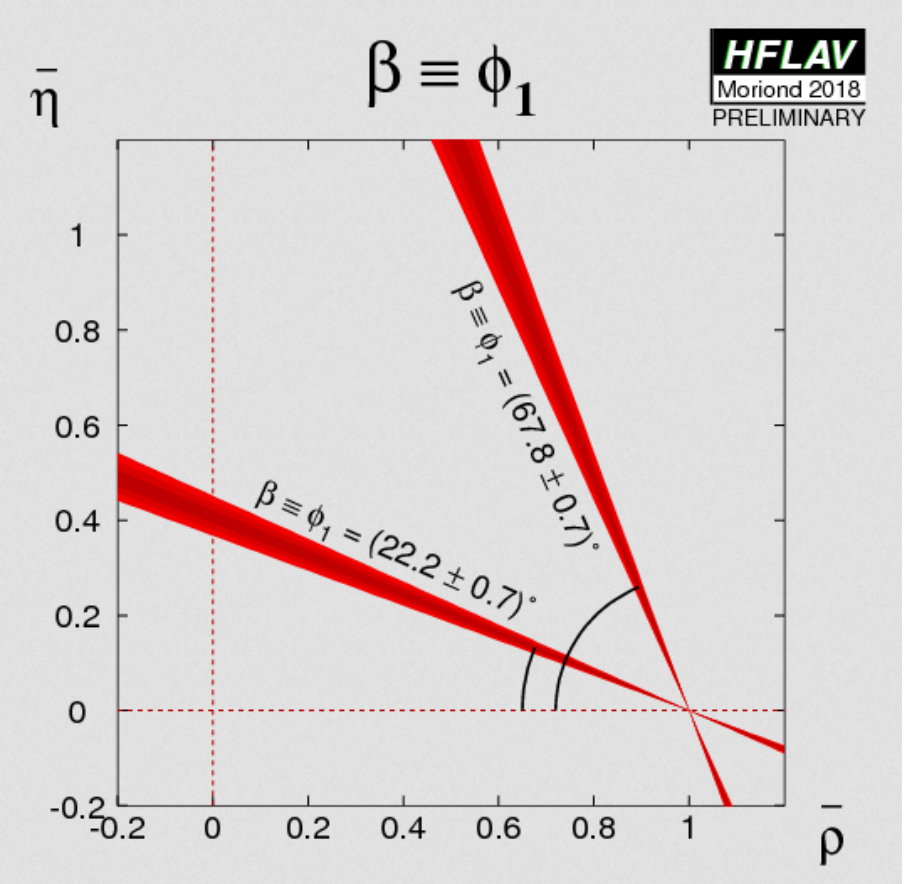


Ambiguity in Φ_1 measurements

- The determination of the angle Φ_1 of the unitarity Triangle from sin $(2\Phi_1)$ measurements lead to a trigonometric ambiguity

This ambiguity can be resolved by measuring the cos $(2\Phi_1)$ from time-dependent analysis of

- $B^0 \to J/\Psi K_S \pi^0$
- $B^0 \to D^{*+} D^{*-} K_S$
- $B^0 \to K_S K^+ K^-$, $B^0 \to K_S \pi^+ \pi^-$
- $B^0 \to D^{(*)} h^0$, $D \to K_S \pi^+ \pi^-$



cos 2β ($B^0 \to J/\psi K^*(892)^0$)

β (ϕ_1) is one of the angles of CMK unitarity triangle, see the review on ``CP'' Violation in the Re

VALUE	DOCUMENT ID			TECN
$1.7^{+0.7}_{-0.9}$	**OUR AVERAGE** Error includes scale factor of 1.6.			
$2.72 \pm^{0.50}_{-0.79} \pm 0.27$	1	AUBERT	2005P	BABR
$0.87 \pm 0.74 \pm 0.12$	2	ITOH	2005	BELL

cos 2β ($B^0 \to [K_S^0 \pi^+\pi^-]_{D^{(*)}} h^0$)

VALUE	DOCUMENT ID			TECN
0.84 ± 0.31	**OUR AVERAGE**			
$1.06 \pm 0.33 \pm^{0.21}_{-0.15}$	1	VOROBYEV	2016	BELL
$0.42 \pm 0.49 \pm 0.16$	2	AUBERT	2007BH	BABR
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.87 \pm^{0.40}_{-0.53} \pm^{0.22}_{-0.32}$	3	KROKOVNY	2006	BELL

Uncertainties are large to solve the trigonometric ambiguity.

Φ_1 measurement in $B^0 \to D^{(*)}h^0$

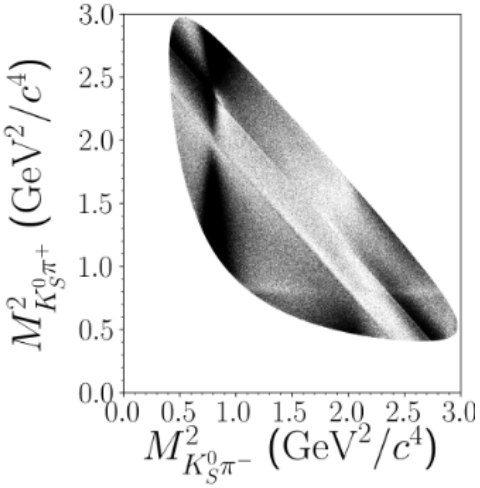
- BaBar and Belle shared their data in a single analysis to resolve this ambiguity using the decay $B^0 \to D^{(*)}h^0$, $D \to K_s\pi^+\pi^-$ and $h^0 = \pi^0, \eta, \omega$
  - $D \to K_s\pi^+\pi^-$ is not a CP eigenstate, rather mixture of CP eigenstate $K_s\rho$, flavor specific $K^{*+}\pi^-$ and $K^{*-}\pi^+$
  - Standard time-dependent CPV measurement does not work
- The approach is similar to the GGSZ method originally proposed for Φ_3 (γ) measurements, adapted by A. Bondar, T. Gershon and P. Krokovny for Φ_1. [PLB 624, 1 (2005)]

$B^0 \to D^{(*)}h^0$ ($D \to K^0_S\, \pi^+\pi^-$) decay rate:

$$\frac{e^{-|\Delta t|/\tau_{B^0}}}{2}\Big[(|\mathcal{A}_{\bar{D}^0}|^2 + |\mathcal{A}_{D^0}|^2) - q(|\mathcal{A}_{\bar{D}^0}|^2 - |\mathcal{A}_{D^0}|^2)\cos(\Delta m_d \Delta t) + 2q\eta_{h^0}(-1)^L \boxed{\mathrm{Im}(e^{-2i\phi_1}\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0})}\sin(\Delta m_d \Delta t)\Big]$$

$$\mathrm{Im}(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0})\,\underline{\cos 2\phi_1} - \mathrm{Re}(\mathcal{A}_{D^0}\mathcal{A}^*_{\bar{D}^0})\sin 2\phi_1$$

$\mathcal{A}_{D^0}, \mathcal{A}_{\bar{D}^0}$:
Decay amplitude as function of Dalitz plot variables $M^2_{K_s\pi^\pm}$
→ Determined using large number of flavor-specific decay $D^{*+} \to D^0\pi^+$ in $c\bar{c}$ event.

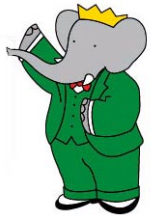


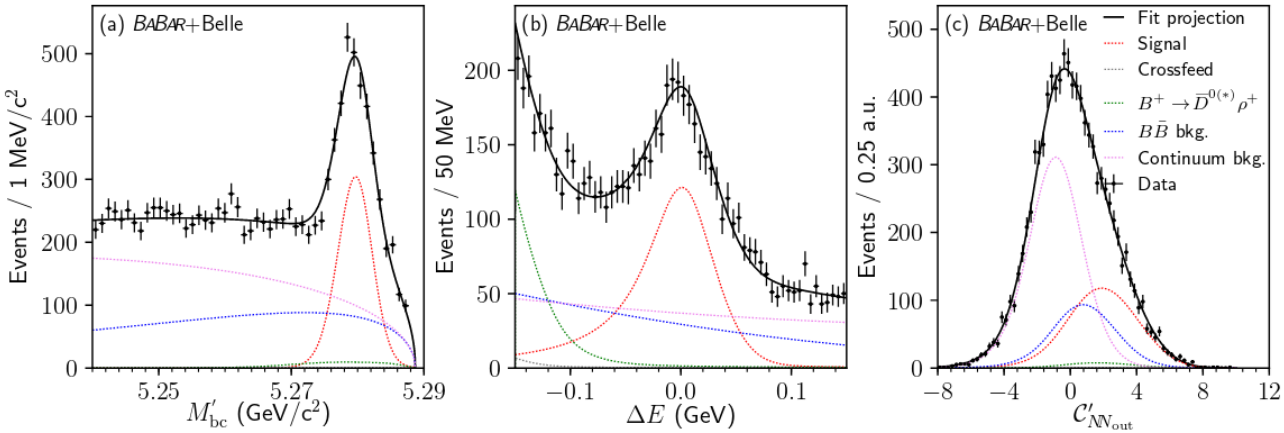
Interference between D^0 and $\bar{D}^0$, and the strong phase variations over the Dalitz plot give us the access to cos ($2\Phi_1$).

924/fb Belle data is used for D^0 Dalitz model

Φ_1 measurement in $B^0 \to D^{(*)}h^0$

- $D^0 h^0$, with h^0 in
  - ✓ $\pi^0 \to \gamma\gamma$
  - ✓ $\eta \to \gamma\gamma,\ \pi^+\pi^-\pi^0$
  - ✓ $\omega \to \pi^+\pi^-\pi^0$
- $D^{*0} h^0$ with
  - ✓ $D^{*0} \to D^0\pi^0$
  - ✓ $h^0 \in \{\pi^0, \eta\}$





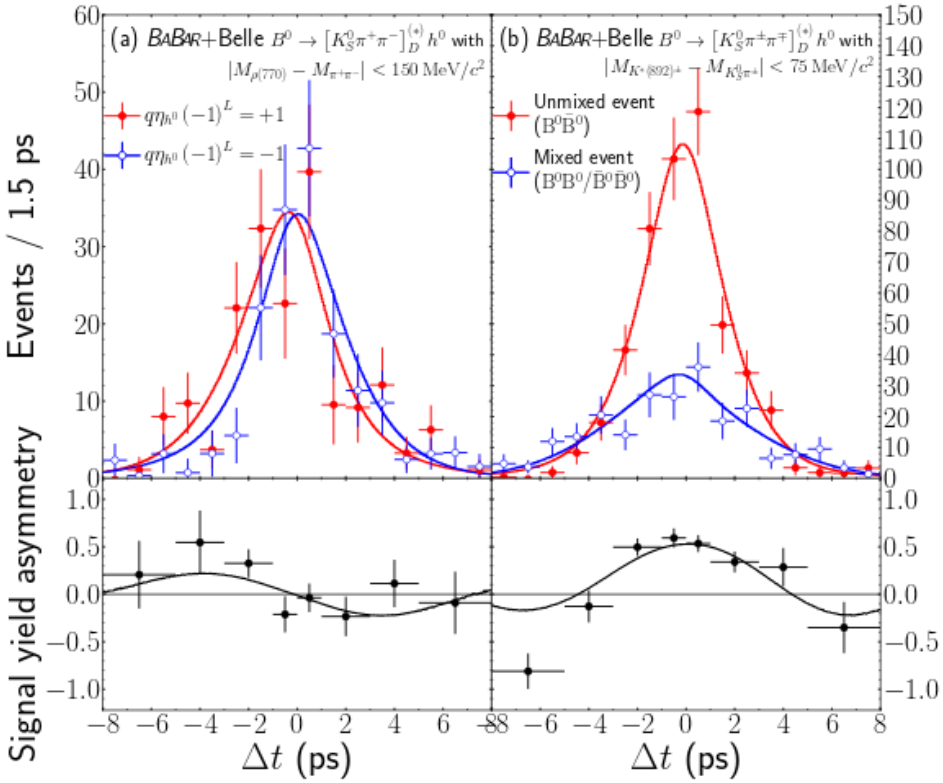
1129 ± 48 events for BaBar

1567 ± 56 events for Belle

CP eigenstate final states →

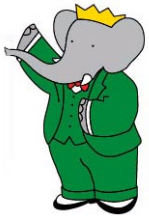
← Flavor-specific final states

Interference between B^0 and $\bar{B}^0$ → time-dependent *CPV* with characteristic pattern as in sin(2β) measurements



No interference between B^0 and $\overline{B^0}$ and no TDCPV arises. The time evolution is governed by B^0-$\overline{B^0}$ oscillations of the entangled $B^0\overline{B^0}$ pairs from Υ(4S) decays → the corresponding asymmetry is a cosine oscillation

Φ_1 measurement in $B^0 \to D^{(*)}h^0$



$$\sin(2\Phi_1) = 0.80 \pm 0.14\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.03\,(\text{model})$$
$$\cos(2\Phi_1) = 0.91 \pm 0.22\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.07\,(\text{model})$$
$$\blacksquare\!\!\blacktriangleright\ \Phi_1 = 22.5 \pm 4.4\,(\text{stat.}) \pm 1.2\,(\text{syst.}) \pm 0.6\,(\text{model})$$

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arXiv:1804.06152[hep-ex]
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- Single most precise measurement of cos $(2\Phi_1)$
- First evidence for cos $(2\Phi_1) > 0$ @ 3.7σ
- Direct exclusion of the 2nd solution [$\pi/2 - \Phi_1 = (68.1 \pm 0.7)^o$] of the CKM unitarity triangle @ 7.3σ
- Observation of CP violation in $B^0 \to D^{(*)}h^0$ @ 5.1σ

Summary

- Using final set of Belle data, we have measured
  - the branching fraction and CP asymmetries of $B^0 \to J/\psi\pi^0$ decays

$$\mathcal{B} = (1.55 \pm 0.10\,^{+0.06}_{-0.07}) \times 10^{-5}$$ ►[most precise to date]

$$\mathcal{S} = -0.59 \pm 0.19 \pm 0.03$$ ►[consistent with measurement from b→ ccs and 3.2σ away from BaBar measurement]

$$\mathcal{A} = -0.15 \pm 0.14\,^{+0.04}_{-0.03}\,,$$

  - CP asymmetries of charmless $B^0 \to K_S\pi^0\pi^0$ decays

$$\sin 2\phi_1^{\rm eff} = 0.92^{+0.27}_{-0.31}\ (\text{stat.})\ ^{+0.10}_{-0.11}\ (\text{syst.})$$ ►[consistent with measurement from b→ ccs]

$$\mathcal{A} = 0.28 \pm 0.21\ (\text{stat.})\ \pm 0.04\ (\text{syst.})$$

- From a joint BaBar + Belle analysis of $B^0 \to D^{(*)}h^0$, we have measured

$$\sin(2\Phi_1) = 0.80 \pm 0.14\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.03\,(\text{model})$$ ►[Observation of CPV @5.1σ]

$$\cos(2\Phi_1) = 0.91 \pm 0.22\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.07\,(\text{model})$$ ►[Evidence of cos $(2\Phi_1) > 0$ @3.7σ]

■► $$\Phi_1 = 22.5 \pm 4.4\,(\text{stat.}) \pm 1.2\,(\text{syst.}) \pm 0.6\,(\text{model})$$ ►[Exclusion of the second solution @7.3σ]