CP Violation in *B* Decays at Belle

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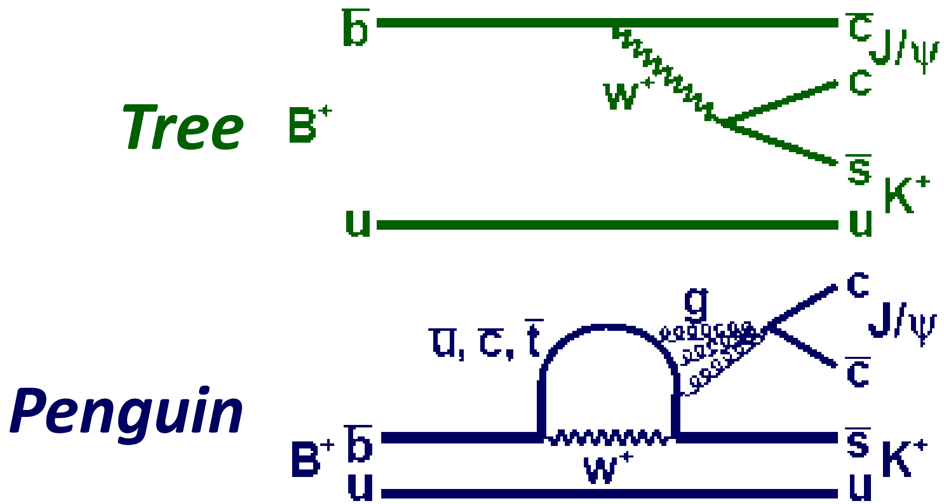
Contents

- *CP* violation measurement in $B^+ \rightarrow J/\psi K^+$ ← ***New***
- *CP* violation measurement in $B^0 \rightarrow K^+K^-K_S^0$
- Status of $\sin 2\phi_1$ measurement in $b \rightarrow c\bar{c}s$ modes

  ↑ ***Stay tuned***
- Summary

CP Violation in $B^+ \to J/\psi K^+$

- **Physics motivation**



Previous measurements of $A_{CP}(B^+ \to J/\psi K^+)$ [%]

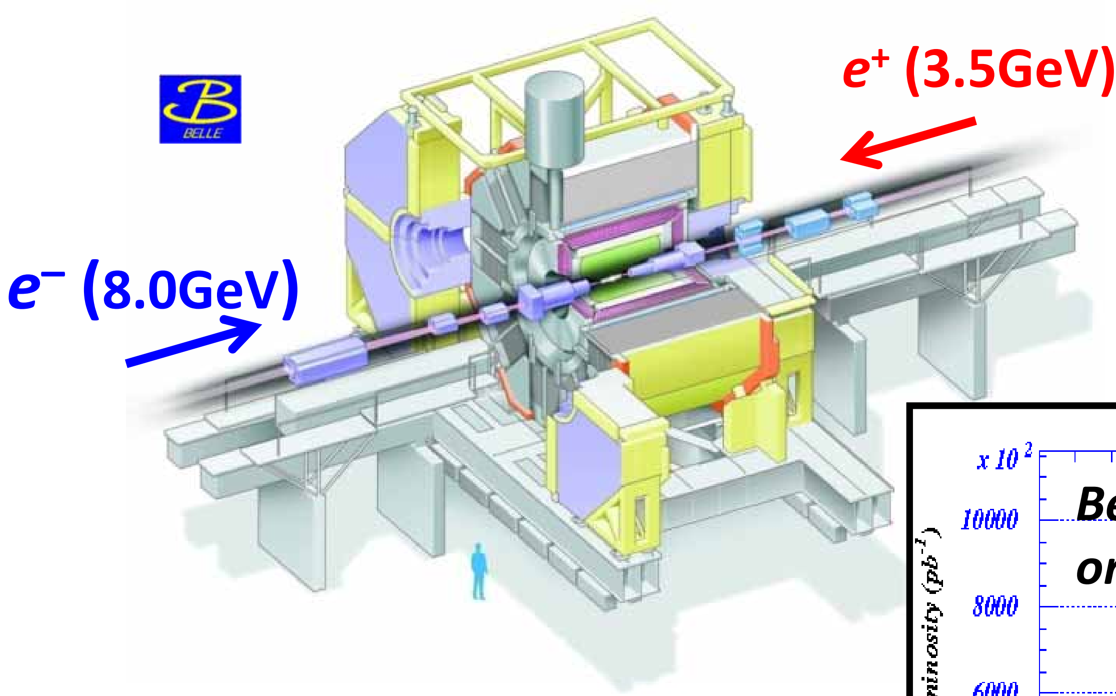
Belle	$-2.6 \pm 2.2 \pm 1.7$	Phys. Rev. D**67**, 032003 (2003)
BABAR	$+3.0 \pm 1.4 \pm 1.0$	Phys. Rev. Lett. **94**, 141801 (2005)
D0	$+0.75 \pm 0.61 \pm 0.30$	Phys. Rev. Lett. **100**, 211802 (2008)
W/A	$+0.9 \pm 0.8$ (PDG2009)	

- The $B^+ \to J/\psi K^+$ decay mediated by the $b \to s$ u-penguin has a different weak phase from the tree.
- The interference between the tree and penguin can cause the direct *CP* violation in $B^+ \to J/\psi K^+$.

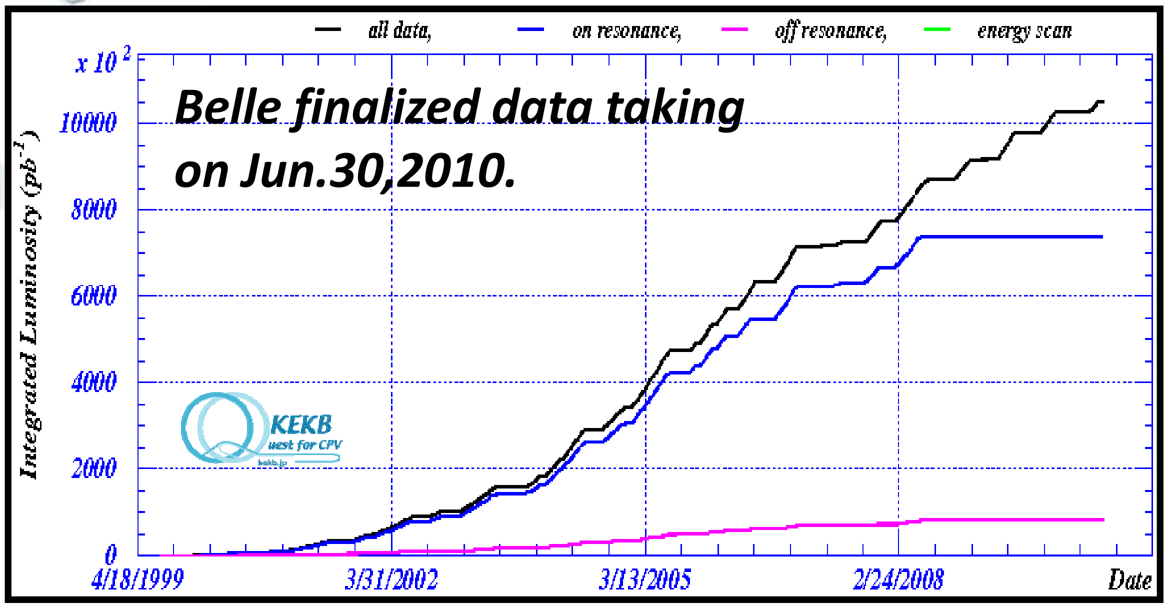
$$A_{CP}(B^+ \to J/\psi K^+) = \frac{Br(B^- \to J/\psi K^-) - Br(B^+ \to J/\psi K^+)}{Br(B^- \to J/\psi K^-) + Br(B^+ \to J/\psi K^+)}$$

CP Violation in $B^+ \to J/\psi K^+$

- **Data sample: 772 x 10^6 $B\bar{B}$ pairs at Υ(4*S*) resonance**
  - The final Belle data sample.

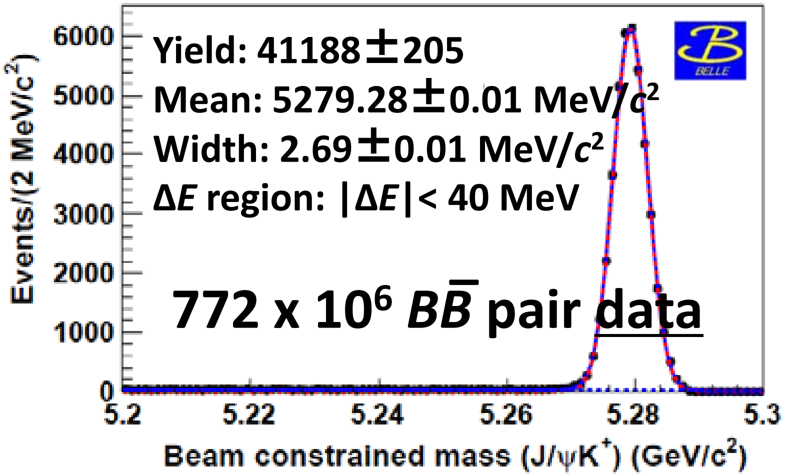


Total recorded luminosity by Belle
1052.79 fb^{-1} > 1ab^{-1}



Raw Asymmetry in $B^+ \to J/\psi K^+$

- **$B^\pm \to J/\psi K^\pm$ event reconstruction**
  - $B^\pm$ candidates are reconstructed from J/ψ and $K^\pm$.



For $K^\pm$(average), 80.5% K efficiency and 9.6% π fake rate.

K-π likelihood ratio

$$\mathcal{R}_K \equiv \frac{\mathcal{L}_K}{\mathcal{L}_K + \mathcal{L}_\pi} > 0.6$$

Signal = single Gaussian

Background = ARGUS BG

Peaking BG is negligibly small → systematic uncertainty.

- **Raw asymmetry: A_{CP}^{raw}**
  - Measured raw asymmetry, which still includes K^+/K^- charge asymmetry in detection, is: $A_{CP}^{raw} = (-0.33 \pm 0.50)\%$
    - The "raw asymmetry" is obtained from yields of the $B^+ \to J/\psi K^+$ and the $B^- \to J/\psi K^-$ in a signal region.

K^+/K^- Charge Asymmetry

- **K^+/K^- charge asymmetry in detection: A_ε^{K+}**
  - The K^+/K^- charge asymmetry in detection arises due to
    - Non-symmetric detector geometry,
    - Different interaction rates in material of K^+/K^-, and
    - Different KID efficiencies of K^+/K^-.

- **The raw asymmetry A_{CP}^{raw} should be corrected for by the K^+/K^- charge asymmetry A_ε^{K+}.**

K^+/K^- Charge Asymmetry Estimation

- **K^+/K^- charge asymmetry estimation**
  - The K^+/K^- detection asymmetry is estimated using the $D_s^+ \to \phi[K^+K^-]\pi^+$ and $D^0 \to K^-\pi^+$, and their charge conjugate.

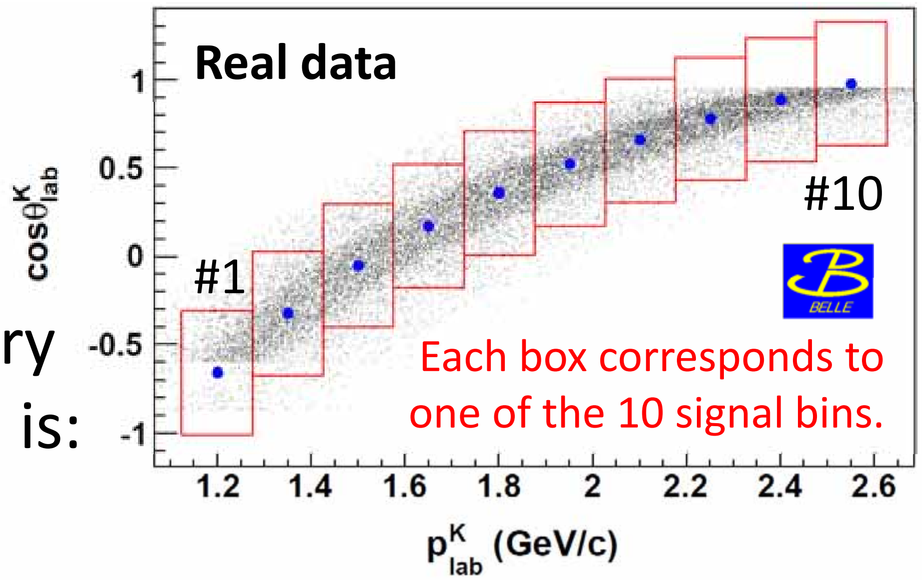
$$\left(A^{x^+} \equiv \frac{N(x^+) - N(x^-)}{N(x^+) + N(x^-)} \right)$$

$$A_{\text{rec}}^{D_s^+} = A_{\text{FB}}^{D_s^+} + A_{\varepsilon}^{\pi^+}$$

$$A_{\text{rec}}^{D^0} = A_{\text{FB}}^{D^0} + A_{\varepsilon}^{\pi^+} - A_{\varepsilon}^{K^+}$$

$$\Rightarrow \quad A_{\text{rec}}^{D_s^+} - A_{\text{rec}}^{D^0} = A_{\varepsilon}^{K^+} \text{ assuming } A_{\text{FB}}^{D_s^+} = A_{\text{FB}}^{D^0}$$

The K^+/K^- charge asymmetry depends on the $\cos\theta^K_{\text{lab}}$ and p^K_{lab}. We bin the signal regions in the ($\cos\theta^K_{\text{lab}}$, p^K_{lab}) plane into 10 boxes, and measure the charge asymmetry for each bin.



- Estimated K^+/K^- charge asymmetry in detection (averaged over bins) is:
  $A_{\varepsilon}^{K+} = (-0.43 \pm 0.07 \pm 0.17)\%$

CP Violation Measurement in $B^+ \to J/\psi K^+$

to be submitted to PRD

- **Fit result**
  - From the sum of A_{CP}^{raw} and A_{ε}^{K+}, we preliminarily determine

$$A_{CP}\left(B^{\pm} \to J/\psi K^{\pm}\right) = (-0.76 \pm 0.50 \pm 0.22)\%$$

772 x 10^6 $B\bar{B}$ pairs

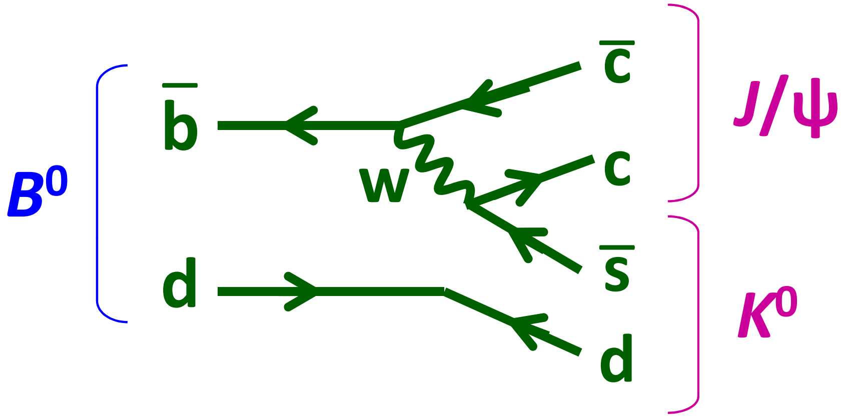
Belle preliminary

  - We observe no significant *CP* violation in $B^+ \to J/\psi K^+$.

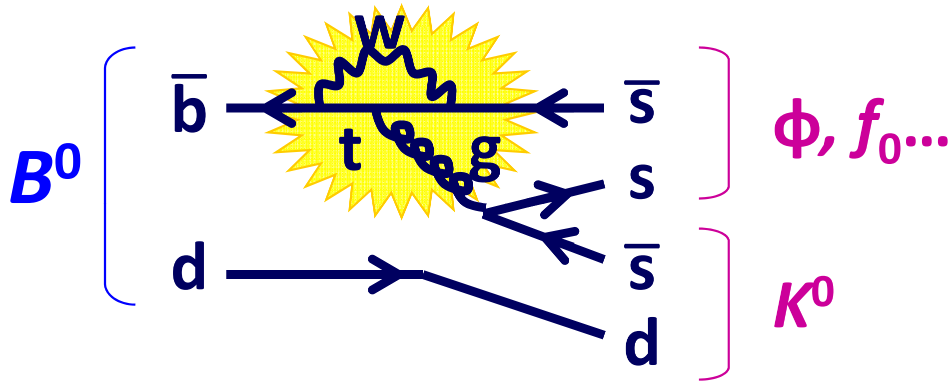
- **Systematic uncertainty**
  - The most dominating source to the systematic uncertainty is $D_s^+ \to \phi\pi^+$ statistics (0.17%).

$b \to sq\bar{q}$ Time-Dependent *CP* Violation

- Physics motivation for the *CP* violation measurement in the $b \to sq\bar{q}$ transition



$S = \sin 2\phi_1$, $A \approx 0$



$S = \sin 2\phi_1^{\mathrm{eff}}$, $A \approx 0$

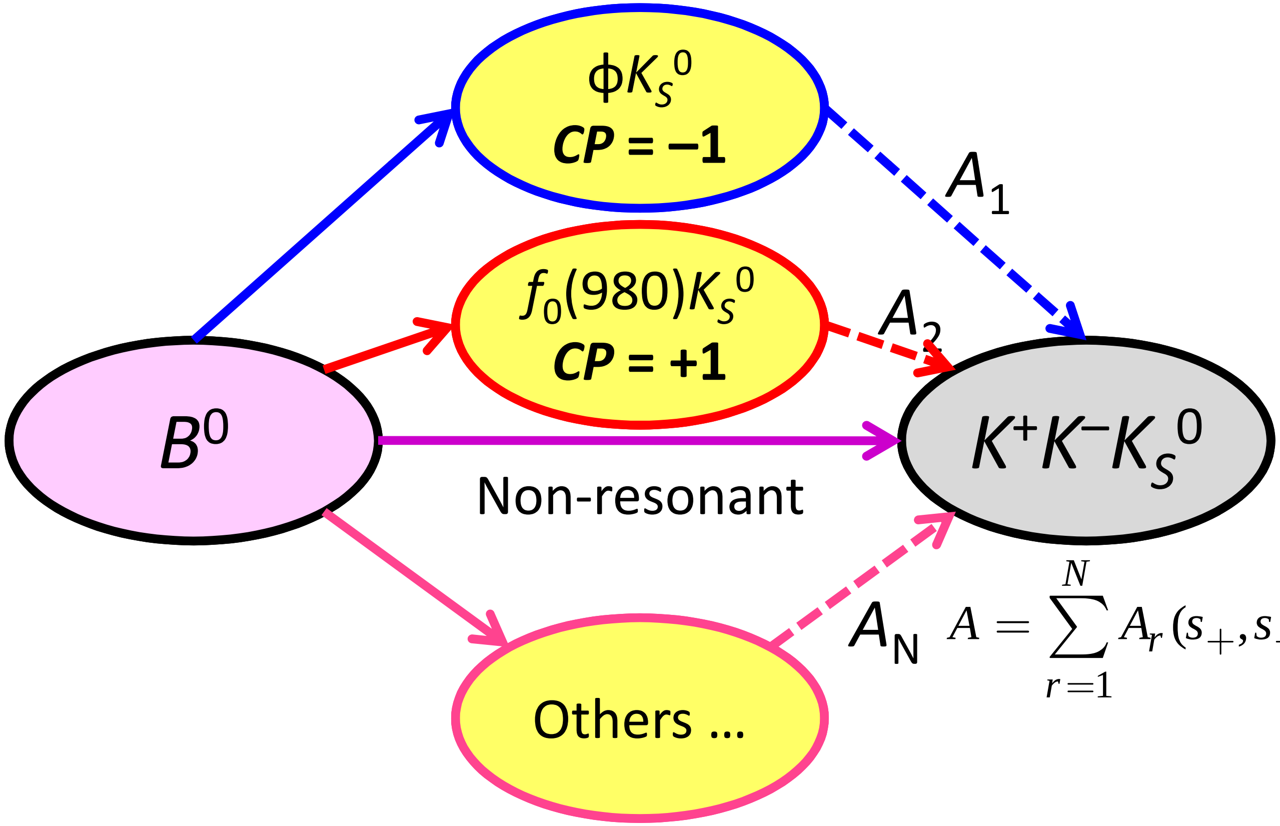
In case of an extra *CP* phase from NP in the penguin loop ⇒

$$\delta \sin 2\phi_1 = \sin 2\phi_1^{\mathrm{eff}} - \sin 2\phi_1 \neq 0$$

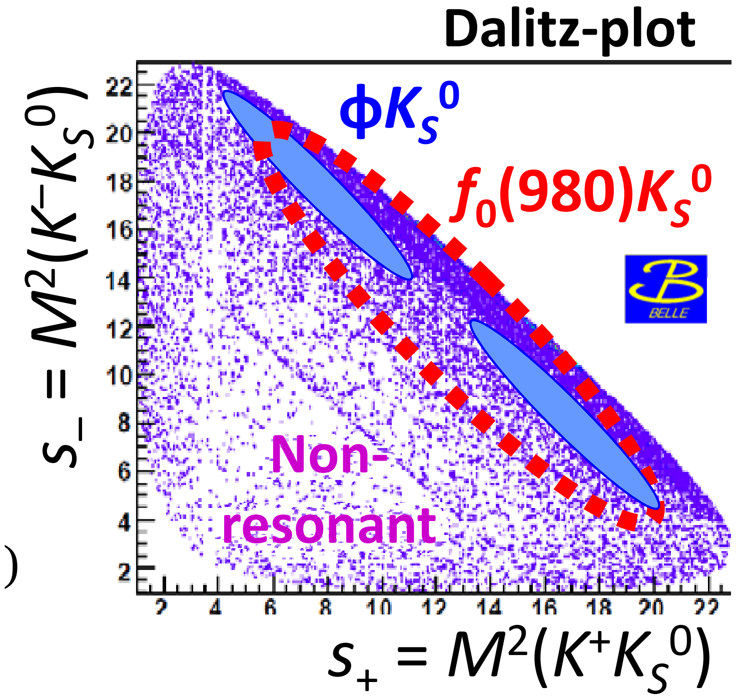
Interference in $B^0 \to K^+K^-K_S^0$ Final State

- **$B^0 \to K^+K^-K_S^0$ final state has several different paths.**
  - Fit to the Dalitz plot is need for the correct CPV measurement.

Dalitz plot



$$A = \sum_{r=1}^{N} A_r(s_+, s_-)$$



Interference in $B^0 \to K^+K^-K_S^0$ Final State

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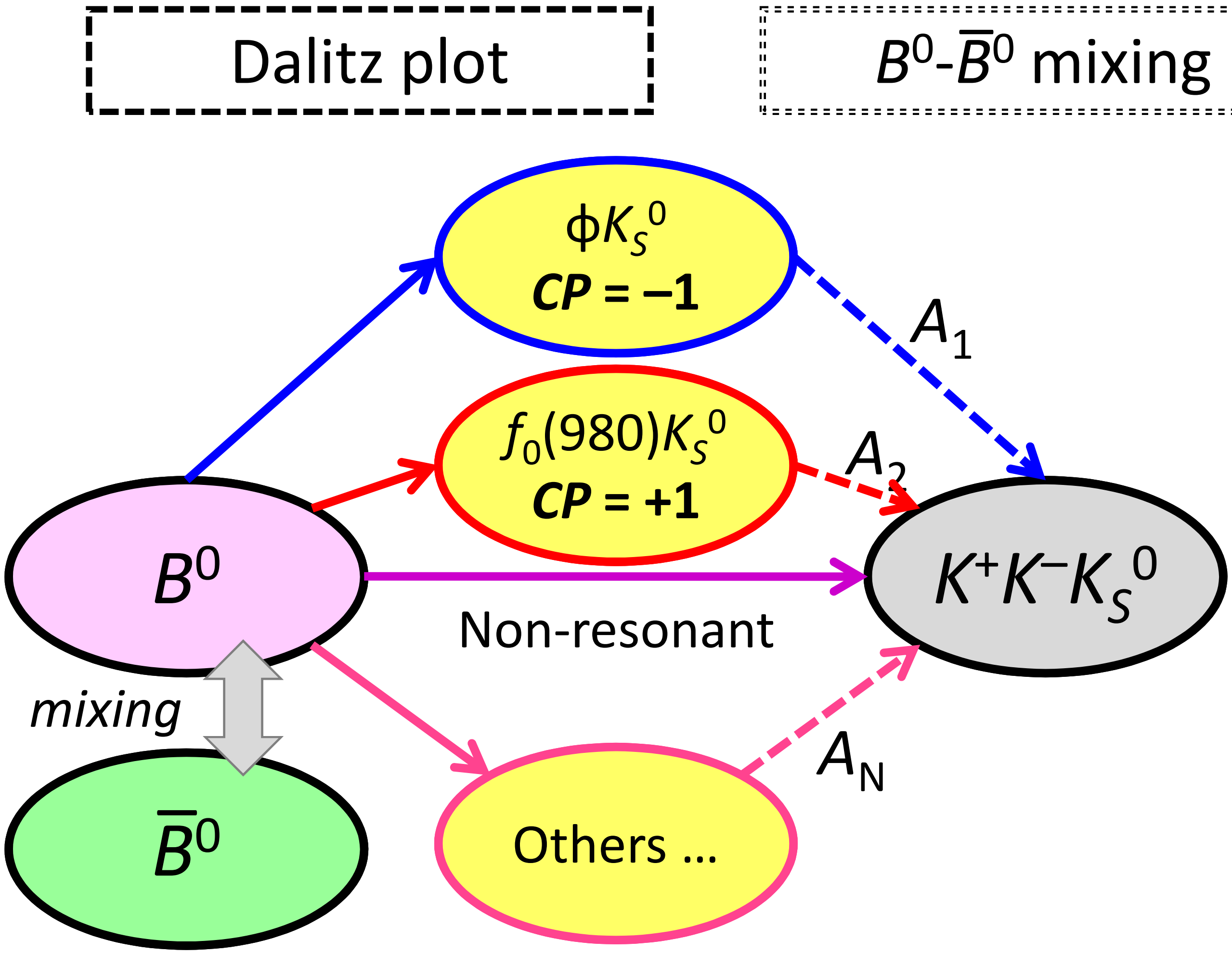

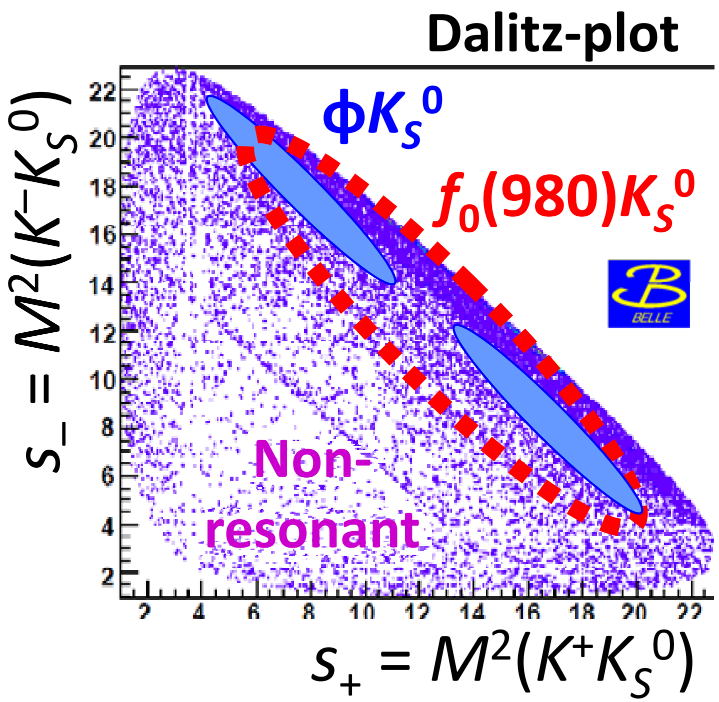

Interference in $B^0 \to K^+K^-K_S^0$ Final State

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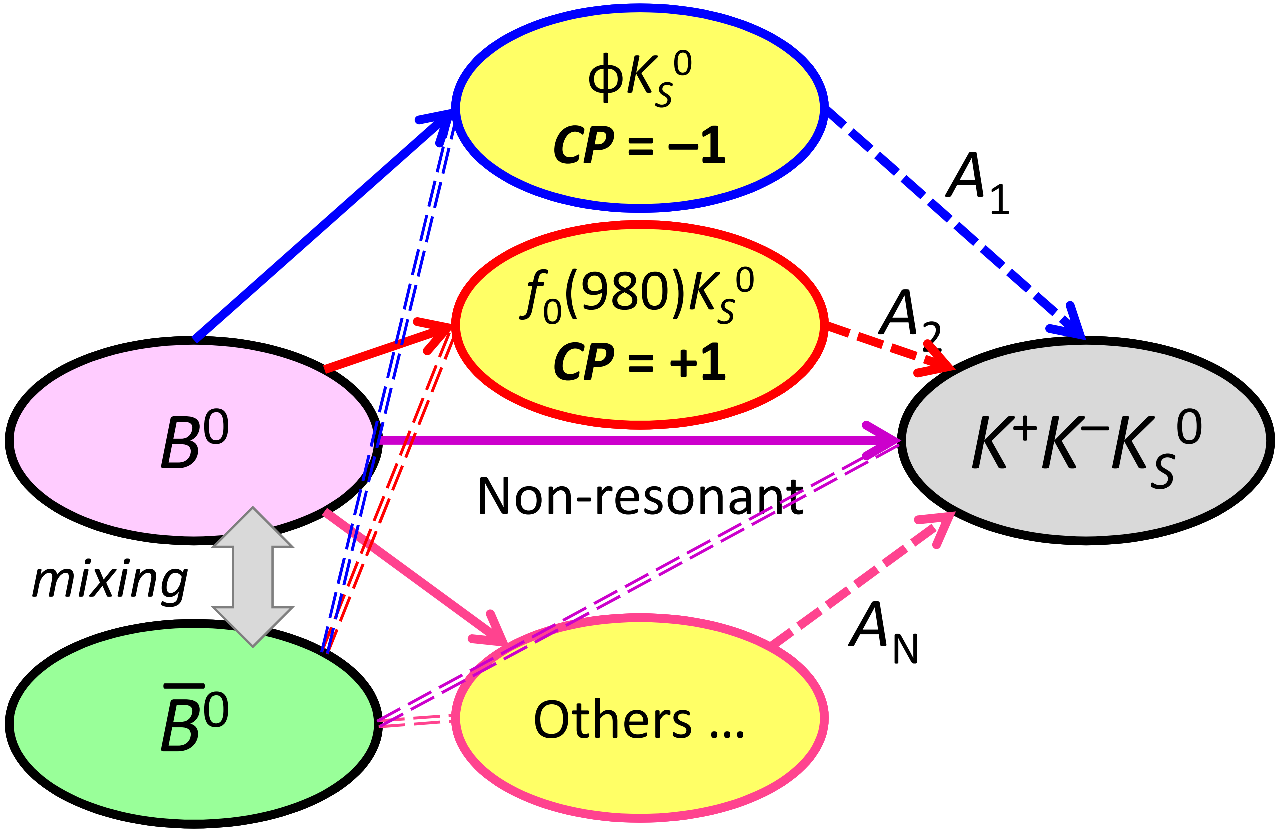
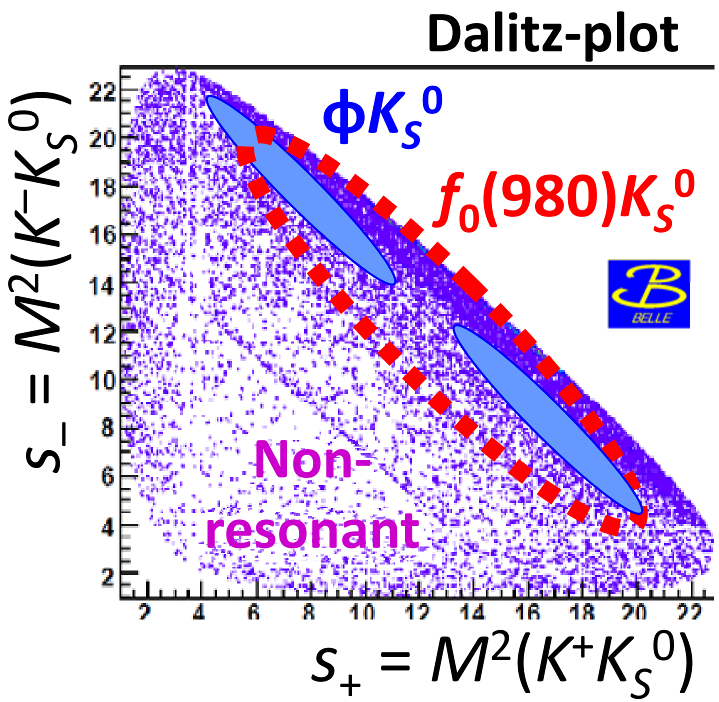
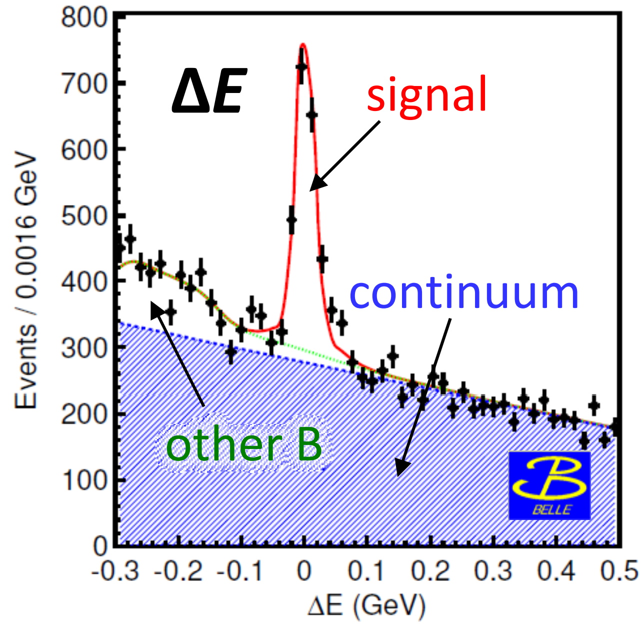
Dalitz plot + B^0-$\overline{B}^0$ mixing → CPV measurement

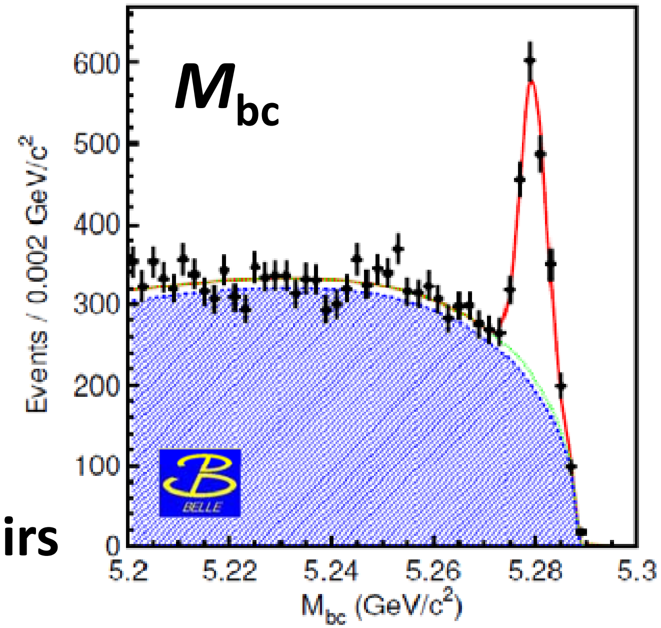




$B^0 \rightarrow K_S^0 K^+ K^-$ Reconstruction

- **# of reconstructed events**
  - Estimation by unbinned-maximum-likelihood fit to the ΔE-M_{bc} distribution
- **$B^0 \rightarrow K_S^0 K^+ K^-$ signal = 1176±51**
  - Reconstruction efficiency ~16%
- **Background**
  - **Continuum ~ 47%**
  - **Other B decays ~ 3%**
  - Signal purity ~ 50%





from 657 x 10^6 $B\bar{B}$ pairs

CP Violation Measurement in $B^0 \to K_S^0 K^+ K^-$

- **The (ϕ_1, *A*) are determined by an unbinned-ML fit onto the time-dependent Dalitz distribution.**
  - The signal probability density function:

$$P_{\mathrm{sig}}(\Delta t, q; s_+, s_-) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left[\left(|\mathcal{A}|^2 + |\bar{\mathcal{A}}|^2\right) - q\left(|\mathcal{A}|^2 - |\bar{\mathcal{A}}|^2\right)\cos\Delta m_d \Delta t + 2q\mathcal{I}m\left(\bar{\mathcal{A}}\mathcal{A}^*\right)\sin\Delta m_d \Delta t\right]$$

- **Four parameter convergences from the fit**

	Solution #1	Solution #2	Solution #3	Solution #4
$\mathcal{A}_{CP}(f_0(980)K_S^0)$	$-0.30 \pm 0.29 \pm 0.11 \pm 0.09$	$-0.20 \pm 0.15 \pm 0.08 \pm 0.05$	$+0.02 \pm 0.21 \pm 0.09 \pm 0.09$	$-0.18 \pm 0.14 \pm 0.08 \pm 0.06$
$\phi_1^{\mathrm{eff}}(f_0(980)K_S^0)$	$(31.3 \pm 9.0 \pm 3.4 \pm 4.0)^\circ$	$(26.1 \pm 7.0 \pm 2.4 \pm 2.5)^\circ$	$(25.6 \pm 7.6 \pm 2.9 \pm 0.8)^\circ$	$(26.3 \pm 5.7 \pm 2.4 \pm 5.8)^\circ$
$\mathcal{A}_{CP}(\phi(1020)K_S^0)$	$+0.04 \pm 0.20 \pm 0.10 \pm 0.02$	$+0.08 \pm 0.18 \pm 0.10 \pm 0.03$	$-0.01 \pm 0.20 \pm 0.11 \pm 0.02$	$+0.21 \pm 0.18 \pm 0.11 \pm 0.05$
$\phi_1^{\mathrm{eff}}(\phi(1020)K_S^0)$	$(32.2 \pm 9.0 \pm 2.6 \pm 1.4)^\circ$	$(26.2 \pm 8.8 \pm 2.7 \pm 1.2)^\circ$	$(27.3 \pm 8.6 \pm 2.8 \pm 1.3)^\circ$	$(24.3 \pm 8.0 \pm 2.9 \pm 5.2)^\circ$
$\Delta(\ln\mathcal{L})$	-1.568	0	-2.956	-5.155

  - They are statistically consistent with each other.
  - Which is the most preferable solution?

CP Violation Measurement in $B^0 \to K_S^0 K^+ K^-$

- **Solution #1 is most preferred from an external information.**

Intermediate state-by-state fraction

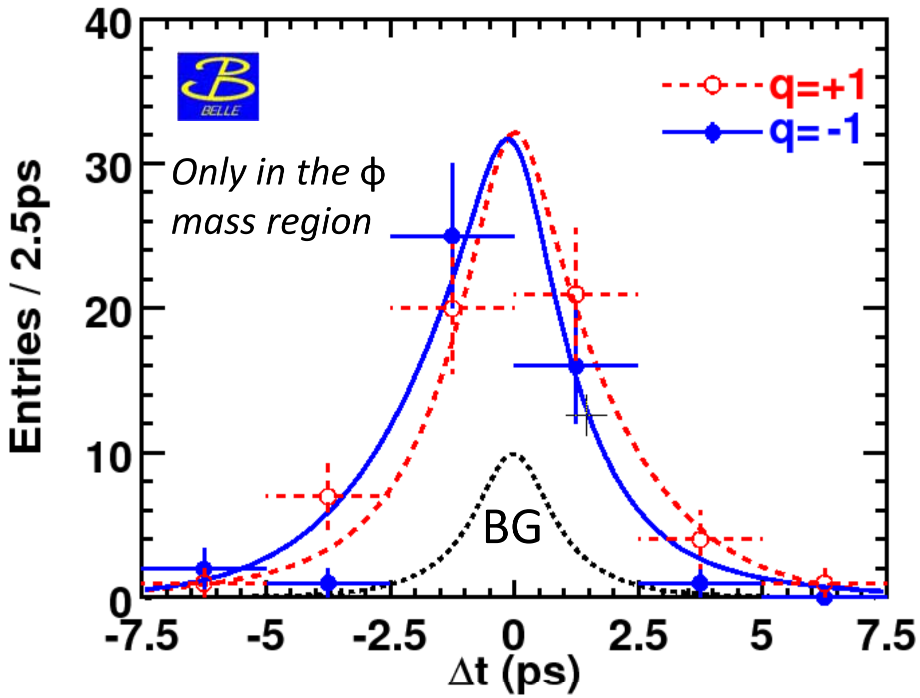
Parameter	Solution 1	Solution 2	Solution 3	Solution 4
$f_{f_0 K_S^0}$	26.0 ± 7.4	54.0 ± 9.6	26.4 ± 7.8	68.1 ± 12.3
$f_{\phi K_S^0}$	14.2 ± 1.2	14.5 ± 1.2	14.2 ± 1.2	14.4 ± 1.2
$f_{f_X K_S^0}$	5.10 ± 1.39	5.89 ± 1.86	39.6 ± 2.6	59.0 ± 3.0
$f_{\chi_{c0} K_S^0}$	3.73 ± 0.74	3.71 ± 0.73	3.68 ± 0.73	4.15 ± 0.79
$f_{(K^+K^-)_{\rm NR} K_S^0}$	138.4 ± 44.8	175.0 ± 52.6	157.4 ± 29.5	48.1 ± 11.7
$f_{(K_S^0 K^+)_{\rm NR} K^-}$	1.65 ± 4.17	21.0 ± 17.3	4.63 ± 6.76	7.87 ± 4.78
$f_{(K_S^0 K^-)_{\rm NR} K^+}$	26.0 ± 12.9	78.0 ± 36.2	38.6 ± 18.1	6.27 ± 3.81
$F_{\rm tot}$	215.2 ± 47.5	352.0 ± 66.8	284.5 ± 36.3	207.9 ± 18.4

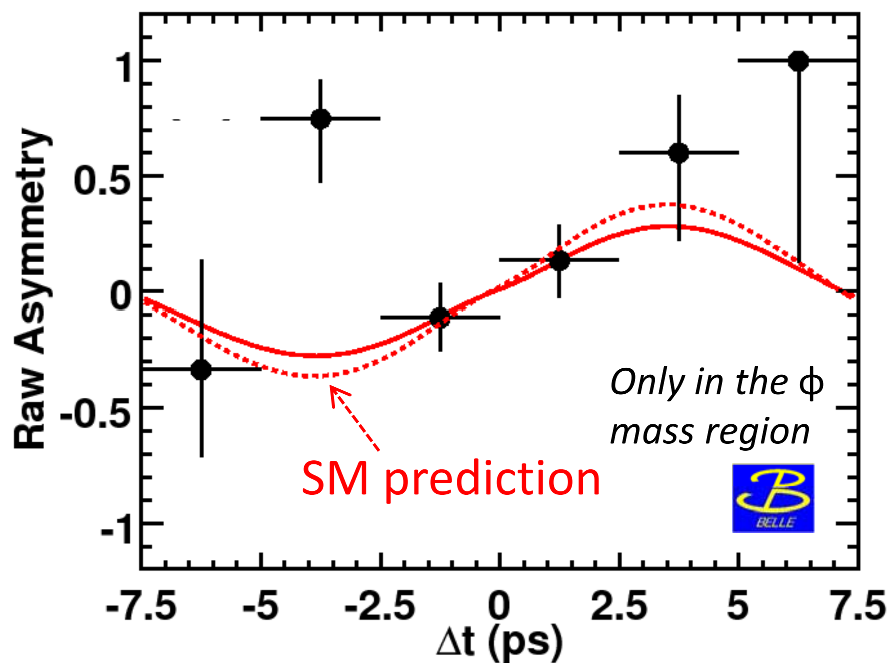
- The $Br(f_0(980) \to \pi^+\pi^-)/Br(f_0(980) \to K^+K^-)$ favors solutions with low $f_0(980)K_S^0$ fraction, when compared to the PDG.
- The $Br(f_0(1500) \to \pi^+\pi^-)/Br(f_0(1500) \to K^+K^-)$ favors solutions with low $f_0(1500)K_S^0$ fraction, when compared to the PDG.
  - Here, we assume f_X as $f_0(1500)$.

CP Violation Measurement in $B^0 \to K_S^0 K^+ K^-$

[solution #1]

submitted to PRD;
hep-ex/1007.3848 (2010)





657 x 10^6^ $B\bar{B}$ pairs

ϕK_S^0	$\phi_1^{\rm eff} = (32.2 \pm 9.0 \pm 2.6 \pm 1.4)^\circ$	$A_{CP} = +0.04 \pm 0.20 \pm 0.10 \pm 0.02$
$f_0(980)K_S^0$	$\phi_1^{\rm eff} = (31.3 \pm 9.0 \pm 3.4 \pm 4.0)^\circ$	$A_{CP} = -0.30 \pm 0.29 \pm 0.11 \pm 0.09$

Belle preliminary

The third error accounts for an uncertainty arises from Dalitz model.

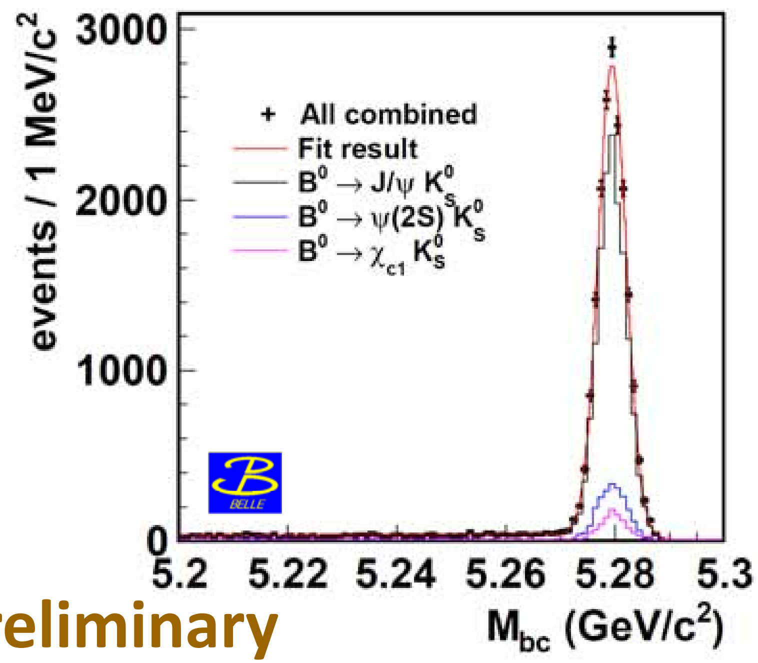
"sin2ϕ_1" Measurement in $b \to c\bar{c}s$

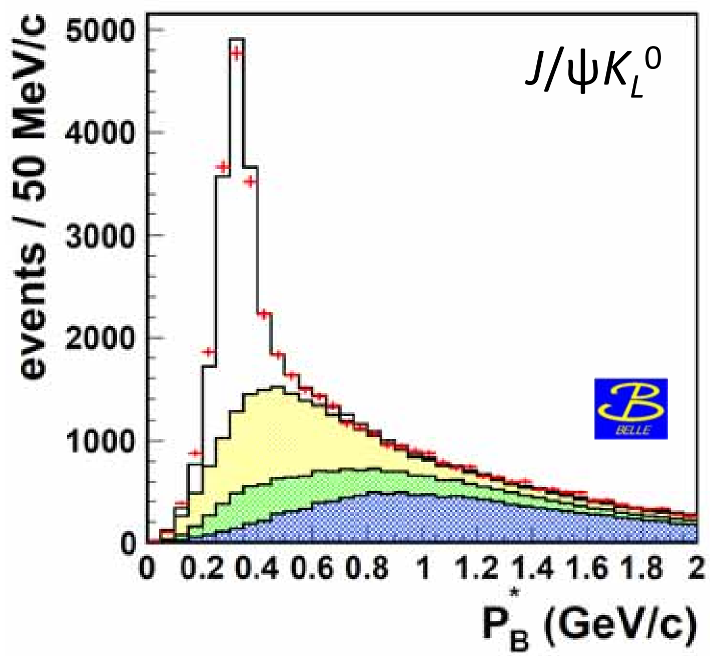
- **Scientific motivations**
  - Test of Kobayashi-Maskawa theory. → *Nobel prize in 2008*
  - Check for a NP phase with very precise unitarity tests.

- **"Social motivations"**
  - *The* final conclusion to the sin2ϕ_1/sin2β from the B-factories over this decade.
  - Establishment of a firm foundation toward the short coming luminosity- frontier era.

$b \to c\bar{c}s$ Reconstruction

from 772 x 10^6 $B\bar{B}$ pairs = final Belle data sample





Belle preliminary

	$J/\psi K_S^0$	$J/\psi K_L^0$	$\psi(2S)K_S^0$	$\chi_{c1}K_S^0$	N_{BB} (x 10^6)
Signal yield ('10)	**12727±115**	**10087±154**	**1981±46**	**943±33**	**772**
Purity ('10) [%]	**97**	**63**	**93**	**89**	
Signal yield ('06)	7484±87	6512±123	–	–	535
Purity ('06) [%]	97	59	–	–	

We have more yields than the N_{BB} increase, for we have improved the track finding algorithm.

Status of "sin2ϕ_1" Measurement

- **We will soon finalize the sin2ϕ_1 in $b \to c\bar{c}s$ modes.**

- **Preliminarily expected statistical sensitivity**

$$\sigma\left(\text{"}\sin 2\phi_1\text{"}\right) \approx 0.024, \quad \sigma\left(A_{CP}\right) \approx 0.016$$

  - Predicted by a signal-yield scale applied to the ICHEP2006 results.
  - The statistical uncertainties are getting close to the systematic ones.

ICHEP2006

***J/ψK*^{0} events in 535 x 10^6 *B$\bar{B}$* pairs**

$$\text{"}\sin 2\phi_1\text{"} = +0.642 \pm 0.031 \pm 0.017$$

$$A_{CP} = +0.018 \pm 0.021 \pm 0.014$$

Summary

- **Using the final Belle data sample (772 x 10^6 $B\bar{B}$ pairs),**
  - we preliminarily determine direct CPV parameter in $B^+ \to J/\psi K^+$:

$J/\psi K^{\pm}$	$A_{CP} = (-0.76 \pm 0.50 \pm 0.22)\%$

  - we are finalizing the measurement of CPV in $b \to c\bar{c}s$ modes; preliminarily expected statistical sensitivities are:

$$\sigma(\text{"}\sin 2\phi_1\text{"}) \approx 0.024, \quad \sigma(A_{CP}) \approx 0.016$$

- **Using 657 x 10^6 $B\bar{B}$ pairs,**
  - we preliminarily determine CPV parameters in $B^0 \to K_S^0 K^+ K^-$:

ϕK_S^0	$\phi_1^{\text{eff}} = (32.2 \pm 9.0 \pm 2.6 \pm 1.4)^{\circ}$	$A_{CP} = +0.04 \pm 0.20 \pm 0.10 \pm 0.02$
$f_0(980) K_S^0$	$\phi_1^{\text{eff}} = (31.3 \pm 9.0 \pm 3.4 \pm 4.0)^{\circ}$	$A_{CP} = -0.30 \pm 0.29 \pm 0.11 \pm 0.09$

Backup Slides

$B^+ \to J/\psi K^+$ Reconstruction

- **$B^\pm \to J/\psi K^\pm$ event reconstruction: J/ψ**
  - J/ψ candidates are reconstructed from e^+e^- or $\mu^+\mu^-$ pairs.
    - (Tightly identified lepton) + (tightly or loosely identified lepton).

Tightly identified *e*
dE/dx && E_{ECL}/p && ECL shower shape

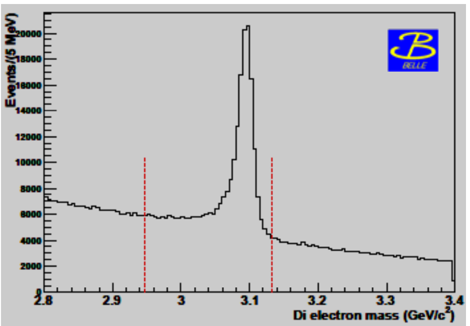
Loosely identified *e*
dE/dx || E_{ECL}/p

Tightly identified μ
\# of penetrating iron plates && shower

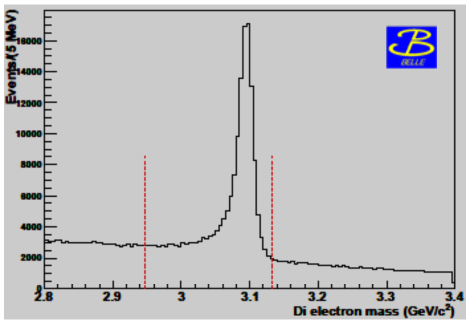
Loosely identified μ
$E_{ECL} \approx E$ deposit by MIP

e^+e^-

tight + loose



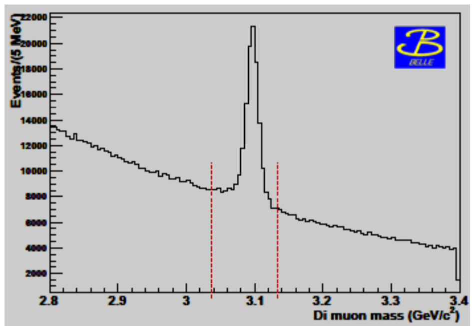
tight + tight



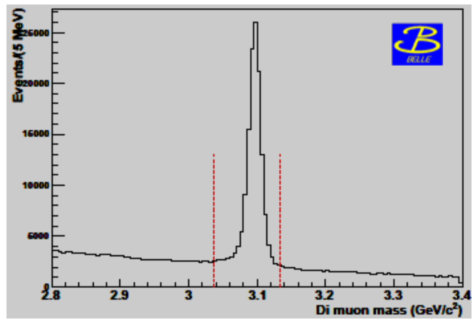
$2.947 < M_{ee} < 3.133$ GeV/c^2

$\mu^+\mu^-$

tight + loose



tight + tight



$3.037 < M_{\mu\mu} < 3.133$ GeV/c^2

CP Violation Measurement in $B^+ \rightarrow J/\psi K^+$

- **List of bin-by-bin *CP* violation and charge asymmetry**

Bin #	A_{CP} (%)	A_{CP}^{raw} (%)	$A_{\varepsilon}^{K^+}$ (%)
1	$+0.75$	$+2.30 \pm 2.47$	$-1.55 \pm 0.35 \pm 0.26$
2	-1.91	-1.04 ± 1.49	$-0.86 \pm 0.24 \pm 0.22$
3	-2.23	-1.65 ± 1.47	$-0.58 \pm 0.23 \pm 0.21$
4	-0.36	$+0.16 \pm 1.46$	$-0.52 \pm 0.22 \pm 0.19$
5	-0.41	$+0.01 \pm 1.46$	$-0.42 \pm 0.21 \pm 0.18$
6	-2.52	-2.19 ± 1.42	$-0.33 \pm 0.20 \pm 0.18$
7	$+1.05$	$+1.04 \pm 1.41$	$+0.01 \pm 0.20 \pm 0.19$
8	-0.14	$+0.20 \pm 1.41$	$-0.35 \pm 0.22 \pm 0.23$
9	-0.23	-0.01 ± 1.57	$-0.22 \pm 0.24 \pm 0.24$
10	-0.63	-0.68 ± 2.61	$+0.05 \pm 0.27 \pm 0.24$
Total	-0.76	-0.33 ± 0.50	$-0.43 \pm 0.07 \pm 0.17$

$B^+ \to J/\psi K^+$ CPV Systematic Uncertainty

- **List of the systematic-uncertainty sources**

	Source	%
A_{CP}^{raw}	Peaking background	0.01
	ARGUS background	0.022
	M_{bc} bin width	0.001
	$(p_{\mathrm{lab}}^{K}, \cos\theta_{\mathrm{lab}}^{K})$ binning	0.022
$A_{\mathrm{rec}}^{D_s^+}$	$D_s^{\pm} \to \phi\pi^{\pm}$ statistics	0.17
	$M_{\phi\pi^+}$ bin width	0.004
	$M_{\phi\pi^+}$ mass window	0.015
	$\cos\theta_{\mathrm{CMS}}^{D_s^{\pm}}$ binning	0.02
	$\cos\theta_{\mathrm{lab}}^{\pi^{\pm}}$ binning	0.07
	$p_{\mathrm{lab}}^{\pi^{\pm}}$ binning	0.04
	No-entry bins	0.001
	$\phi \to K^+K^-$ asymmetry	0.05
$A_{\mathrm{rec}}^{D^0}$	$D^0(\bar{D}^0) \to K^{\mp}\pi^{\pm}$ statistics	0.07
	$M_{K^-\pi^+}$ bin width	0.002
	$M_{K^-\pi^+}$ mass window	0.005
	$(p_{\mathrm{lab}}^{K}, \cos\theta_{\mathrm{lab}}^{K})$ binning	0.039
	$A_{CP}^{D^0}$	0.01
	$A_{\mathrm{FB}}^{D_s^+} = A_{\mathrm{FB}}^{D^0}$ assumption	0.01
	Total	0.22

$B^0 \to K_S^0 K^+ K^-$ CPV Systematic Uncertainty

- **List of the systematic-uncertainty sources**

for the solution #1

	$f_0(980)K_S^0$	$\phi(1020)K_S^0$	others	$f_0(980)K_S^0$	$\phi(1020)K_S^0$	others
Category	$\delta\phi_1^{\rm eff}(^\circ)$			$\delta\mathcal{A}_{CP}$		
Vertex Reconstruction	1.3	1.2	1.1	0.046	0.080	0.024
Wrong tag fraction	0.2	0.2	0.2	0.004	0.006	0.003
Δt resolution function	1.9	1.9	1.5	0.018	0.011	0.010
Possible fit bias	2.2	0.9	0.4	0.067	0.008	0.026
Physics parameters	0.1	0.0	0.1	0.002	0.001	0.001
Background PDF	1.0	0.8	0.8	0.037	0.012	0.016
Signal fraction	0.2	0.4	0.3	0.013	0.006	0.004
Misreconstruction	0.1	0.0	0.0	0.000	0.000	0.001
Efficiency	0.2	0.2	0.1	0.011	0.004	0.005
Signal model	0.7	0.4	0.4	0.040	0.017	0.006
Tag-side interference	0.0	0.0	0.0	0.043	0.054	0.066
Total w/o Dalitz model	3.4	2.6	2.1	0.110	0.100	0.078
Dalitz model	4.0	1.4	2.5	0.089	0.019	0.032