Recent EW results from Belle

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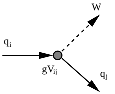
On behalf of Belle collaboration



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

$\nearrow$

.

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

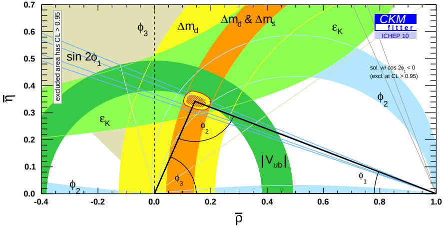
Unitarity triangle:

$$\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} + 1 + \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} = 0$$

$$\phi_1 \equiv \beta = arg \left(\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*} \right)$$

$$\phi_3 \equiv \gamma = arg \left(\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right)$$

Search for NP via measurement of sides and angles of UT.

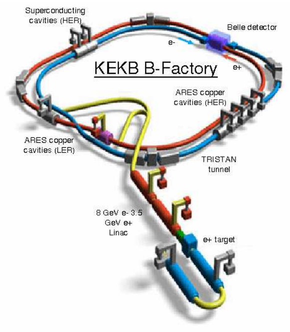


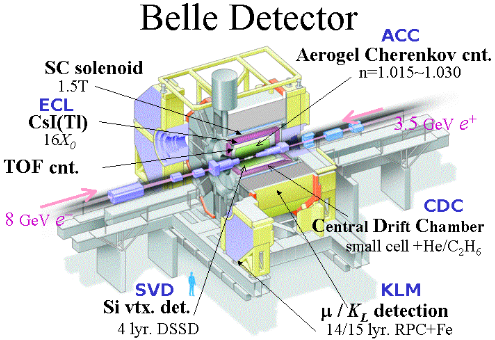
Tension in the CKM fit: $\sim 3\sigma$ between direct and indirect $\sin 2\phi_1$

This talk: two new results from Belle

- Updated $\sin 2\phi_1$ measurement with $B \to (c\bar{c})K^0$
- Measurement of ϕ_3 with model-independent Dalitz plot analysis of $B \to DK$, $D \to K_S^0 \pi\pi$

Belle experiment

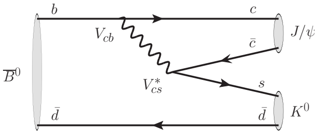


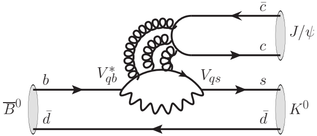


- Belle detector, KEKB collider at KEK laboratory, Tsukuba, Japan
- World record luminosity: $L \simeq 2.1 \times 10^{34}$ cm^{-2}s^{-1} (at $\Upsilon(5S)$).
- Stopped data taking in 2010 $\Rightarrow$ upgrade to Belle II [M. Danilov's talk]
- Final data sample: more than 1 ab^{-1}
  - 711 fb^{-1} at $\Upsilon(4S)$ (772×10^6 $B\overline{B}$ decays)
  - 121 fb^{-1} at $\Upsilon(5S)$
  - $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, energy scans

Time-dependent CP asymmetry in $B \to (c\bar{c})K^0$

Golden mode for CP violation measurement: $B^0 \to J/\psi K^0_S$.
Measure mixing-induced CP violation, $b \to c\bar{c}s$ transition





Penguin diagram is suppressed, has the same weak phase $\Rightarrow$ negligible theoretical uncertainty.
Measure *CP* asymmetric decay time distribution separately for B^0 and $\overline{B}^0$:

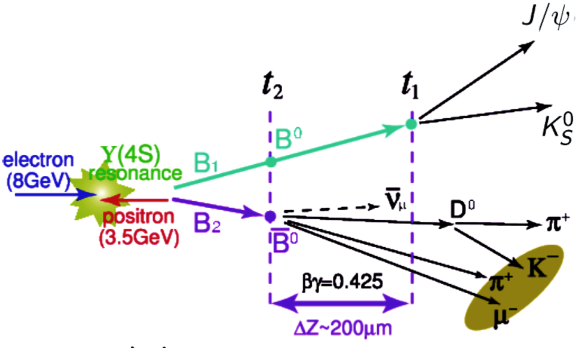
$$p(\Delta t) = \frac{e^{|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \{1 \pm [S_{f_{CP}} \sin(\Delta m_d \Delta t) + A_{f_{CP}} \cos(\Delta m_d \Delta t)]\}$$

In the Standard Model, $S_{f_{CP}} = -\xi_{f_{CP}} \sin 2\phi_1$ — indirect CPV
$A_{f_{CP}} \simeq 0$ — direct CPV.

Last published Belle result: $\sin 2\phi_1 = 0.642 \pm 0.031 \pm 0.017$ (535M $B\overline{B}$)

Flavor tagging and Δt measurement

Machine with asymmetric beam energy.
Δt is measured by z coordinates of vertices of signal B and tagging B
B^0 and $\overline{B}^0$ are in entangled state:
flavor of one B is fixed by another B at the moment of its decay.



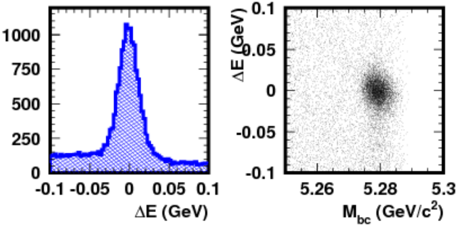
In practice, need to account for the wrong tag probability and vertexing resolution — calibrated with data.

Signal selection

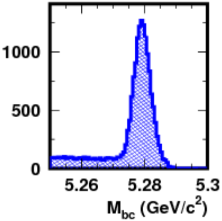
In $\Upsilon(4S)$ decays, pairs of B mesons are produced near threshold.
$E_B = E_{\mathrm{CM}}/2$, small CM momentum (300 MeV/c).

Selection variables:

- CM energy difference
  $\Delta E = \sum E_i - E_{\mathrm{CM}}/2$

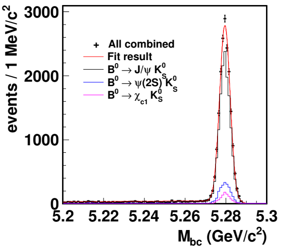


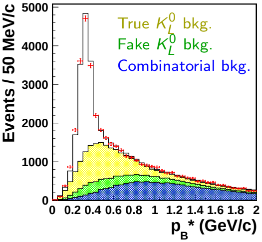
- Beam-constrained mass
  of the B meson:
  $M_{\mathrm{bc}} = \sqrt{(E_{\mathrm{CM}}/2)^2 - (\sum p_i)^2}$



Use 711 fb^{-1} sample (772M $B\bar{B}$ pairs). Belle preliminary

More data, improved tracking $\Rightarrow \sim 50\%$ more statistics than prev. analysis





$CP = -1$ modes:

Mode	Signal yield
$B \to J/\psi K_S^0$, $J/\psi \to l^+l^-$	12681 ± 114
$B \to \psi(2S)K_S^0$, $\psi(2S) \to l^+l^-$	908 ± 31
$\psi(2S) \to J/\psi\pi^+\pi^-$	1072 ± 33
$B \to \chi_{c1}K_S^0$, $\chi_{c1} \to J/\psi\gamma$	943 ± 33

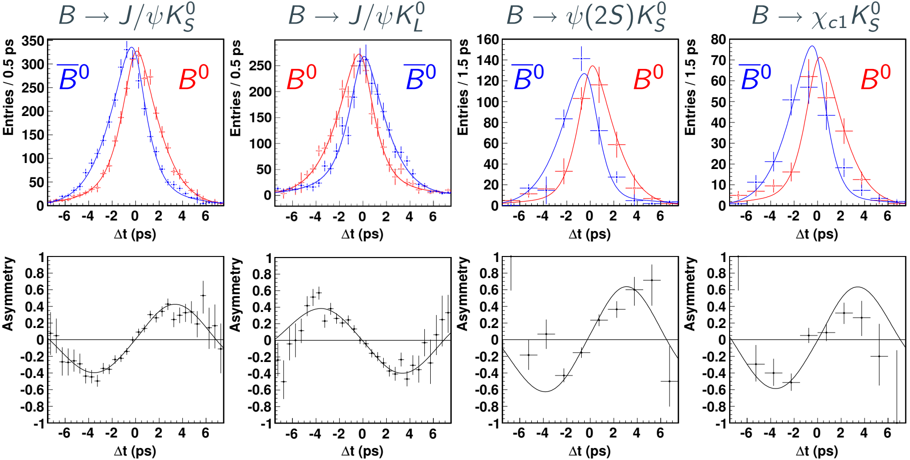
$CP = +1$ mode:

$B \to J/\psi K_L^0$ Signal yield: 10041 ± 154

Missing information about K_L^0 momentum: K_L^0 cluster reconstructed in ECL or KLM, match it with the K_L^0 direction from kinematical constraints.

Good tag only, background subtracted.

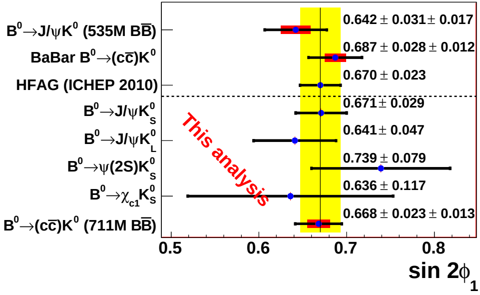
Belle preliminary



$S = 0.671 \pm 0.029$	$S = 0.641 \pm 0.047$	$S = 0.739 \pm 0.079$	$S = 0.636 \pm 0.117$
$A = -0.014 \pm 0.021$	$A = 0.019 \pm 0.026$	$A = 0.103 \pm 0.055$	$A = -0.023 \pm 0.083$

CP violation is observed in all modes

Belle preliminary



Combination of four modes:

$$S = 0.668 \pm 0.023 \pm 0.013\,(\mathrm{syst})$$
$$A = 0.007 \pm 0.016 \pm 0.013\,(\mathrm{syst})$$

Expect tension in CKM fit to be loosened

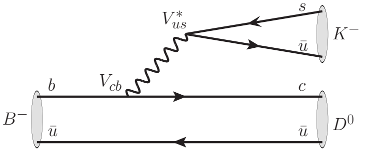
Systematic errors:

	ΔS	ΔA
Vertexing	$^{+0.008}_{-0.009}$	± 0.008
Flavor tagging	$^{+0.004}_{-0.003}$	± 0.003
Resolution function	± 0.007	± 0.001
Physics parameters	± 0.001	< 0.001
Fit bias	± 0.004	± 0.005
$J/\psi K^0_S$ signal fraction	± 0.002	± 0.001
$J/\psi K^0_L$ signal fraction	± 0.004	$^{+0.000}_{-0.002}$
$\psi(2S) K^0_S$ signal fraction	< 0.001	< 0.001
$\chi_{c1} K^0_S$ signal fraction	< 0.001	< 0.001
Background Δt	± 0.001	< 0.001
Tag-side interference	± 0.001	± 0.008
Total	± 0.013	± 0.013

Significant improvement in sys. error (vertexing, resolution function)

Measurement of ϕ_3 in $B \to DK$ decays

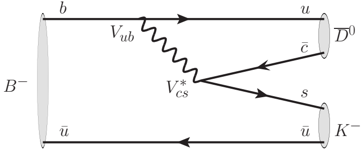
$B^- \to D^0 K^-$:



$A \sim V_{cb} V^*_{us} \sim A\lambda^3$

+

$B^- \to \overline{D}^0 K^-$:



$A \sim V_{ub} V^*_{cs} \sim A\lambda^3(\rho - i\eta)$

If D^0 and $\overline{D}^0$ decay into the same final state: $|\tilde{D}\rangle = |D^0\rangle + re^{i\theta}|\overline{D}^0\rangle$

Relative phase in $B^+ \to DK^+$: $\theta = +\phi_3 + \delta$,

$B^- \to DK^-$: $\theta = -\phi_3 + \delta$.

Ratio of the two amplitudes:

$$r = \left| \frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right| = \left| \frac{V_{ub} V^*_{cs}}{V_{cb} V^*_{us}} \right| \times [\text{Color supp}] \sim 0.1$$

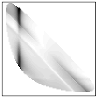
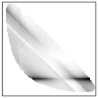
ϕ_3: Dalitz analysis of D decay from $B^\pm \to DK^\pm$

[A. Giri, Yu. Grossman, A. Soffer, J. Zupan, PRD **68**, 054018 (2003)]

[A. Bondar, Belle Dalitz analysis meeting, 24-26 Sep. 2002]

Use $B^\pm \to DK^\pm$ modes with 3-body decay $D \to K_S^0\pi^+\pi^-$.
Dalitz plot density: $d\sigma_\pm(m_+^2, m_-^2) \sim |M_\pm|^2 dm_+^2 dm_-^2$

$$|M_\pm(m_+^2, m_-^2)|^2 = |f_D(m_+^2, m_-^2) + re^{i\delta_B \pm i\phi_3} f_D(m_-^2, m_+^2)|^2$$

$= \Big|$  $+ re^{i\delta_B \pm i\phi_3}$  $\Big|^2$

$\overline{D}^0 \to K_S^0\pi^+\pi^-$ amplitude f_D is extracted from continuum ($D^{*\pm} \to D\pi^\pm$), parametrized as a set of two-body amplitudes.

Only $|f_D|^2$ is observable $\Rightarrow$ Model dependence as a result.

Latest Belle result: $\phi_3 = [78^{+11}_{-12} \pm 4(\mathrm{syst}) \pm 9(\mathrm{model})]^\circ$ (605 fb^{-1})
$r_B = 0.16 \pm 0.04 \pm 0.01(\mathrm{syst})^{+0.05}_{-0.01}(\mathrm{model})$

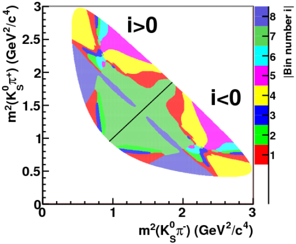
Model error would dominate precise measurements at Super B factories.

ϕ_3: Binned Dalitz plot analysis

Solution: use binned Dalitz plot and deal with numbers of events in bins.

[A. Giri, Yu. Grossman, A. Soffer, J. Zupan, PRD **68**, 054018 (2003)]

[A. Bondar, A. P. EPJ C **47**, 347 (2006); EPJ C **55**, 51 (2008)]



$$M_i^{\pm} = h\{K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(x_{\pm} c_i + y_{\pm} s_i)\}$$

$$x_{\pm} = r_B \cos(\delta_B \pm \phi_3) \quad y_{\pm} = r_B \sin(\delta_B \pm \phi_3)$$

$M_i^{\pm}$: numbers of events in $D \to K_S^0\pi^+\pi^-$ bins from $B^{\pm} \to DK^{\pm}$
K_i: numbers of events in bins of flavor $\overline{D}^0 \to K_S^0\pi^+\pi^-$ from $D^* \to D\pi$.
c_i, s_i contain information about strong phase difference between symmetric Dalitz plot points $(m^2_{K_S^0\pi^+}, m^2_{K_S^0\pi^-})$ and $(m^2_{K_S^0\pi^-}, m^2_{K_S^0\pi^+})$:

$$c_i = \langle\cos\Delta\delta_D\rangle, \quad s_i = \langle\sin\Delta\delta_D\rangle$$

ϕ_3: Obtaining c_i, s_i

Coefficients c_i, s_i can be obtained in $\psi(3770) \to D^0\overline{D}^0$ decays.
Use quantum correlations between D^0 and $\overline{D}^0$.

- If both D decay to $K^0_S\pi^+\pi^-$, the number of events in i-th bin of $D_1 \to K^0_S\pi^+\pi^-$ and j-th bin of $D_2 \to K^0_S\pi^+\pi^-$ is

$$M_{ij} = K_i K_{-j} + K_{-i} K_j - 2\sqrt{K_i K_{-i} K_j K_{-j}}(c_i c_j + s_i s_j).$$

  $\Rightarrow$ constrain c_i and s_i.

- If one D decays to a CP eigenstate, the number of events in i-th bin of another $D \to K^0_S\pi^+\pi^-$ is

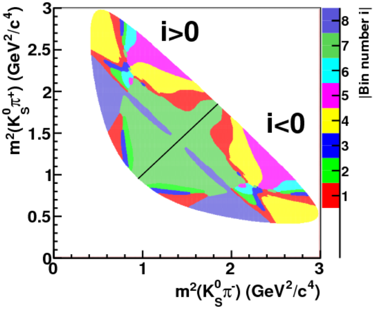
$$M_i = K_i + K_{-i} \pm 2\sqrt{K_i K_{-i}} c_i.$$

  $\Rightarrow$ constrain c_i.

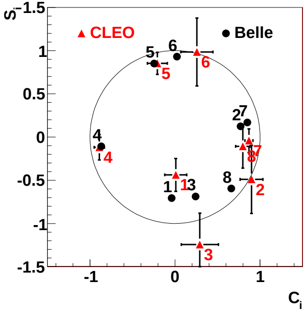
c_i, s_i measurement has been done by CLEO and can be done in future at BES-III.

ϕ_3: Optimal binning and CLEO measurement of c_i, s_i

Binned analysis reduces stat. precision.
Can improve this by choosing a binning inspired by $\overline{D}^0 \to K^0_S \pi^+ \pi^-$ model.
[CLEO collaboration, PRD **82**, 112006 (2010)]



Optimized $\overline{D}^0 \to K^0_S \pi^+ \pi^-$ binning using BaBar 2008 measurement.



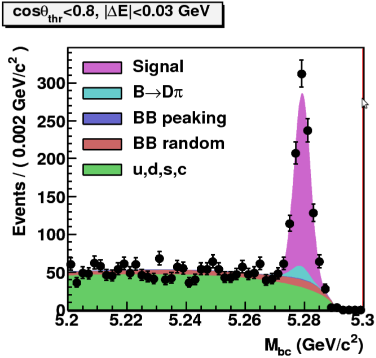
Measured c_i, s_i values and predictions by Belle model

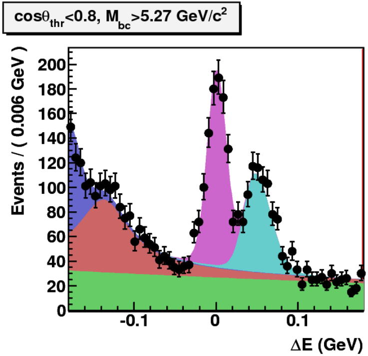
Optimal binning depends on model, but ϕ_3 does not.
Bad model $\Rightarrow$ worse precision, but no bias!

ϕ_3: $B^{\pm} \to DK^{\pm}$, $D \to K^0_S\pi^+\pi^-$ signal selection

Use 711 fb^{-1} sample (772M $B\overline{B}$ pairs). Belle preliminary

Data reprocessed with new tracking $\Rightarrow$ improved efficiency (12% $\to$ 16%)





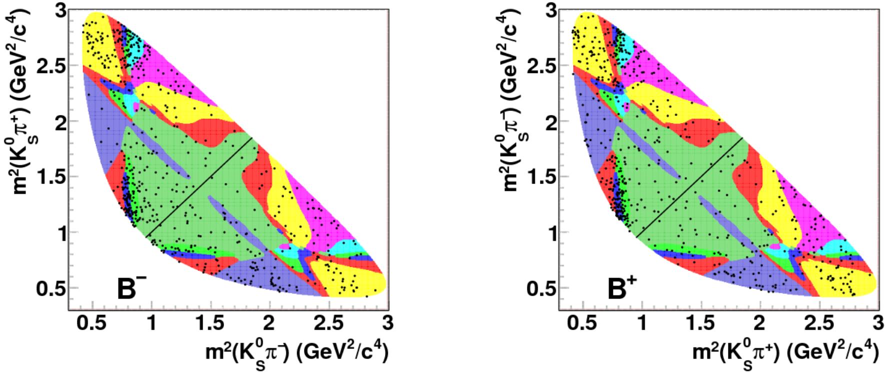
Signal selection variables: M_{bc}, ΔE, event shape ($\cos\theta_{\text{thr}}$, "virtual calorimeter" Fisher discriminant). 4D unbinned fit to get signal yield.

Signal yield: 1176 ± 43 events ($\sim$ 55% more data than in prev. analysis)

ϕ_3: Dalitz plots of $D \to K_S^0\pi^+\pi^-$ decay from $B^\pm \to DK^\pm$

Belle preliminary

$B^- \to D^0K^-$: $B^+ \to D^0K^+$:

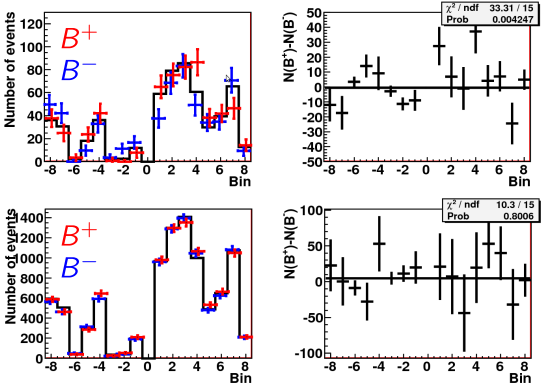


Dalitz plots for signal-enriched region:

($M_{\rm bc} > 5.27$ GeV$/c^2$, $|\Delta E| < 30$ MeV, $\cos\theta_{\rm thr} < 0.8$).

Fit signal selection distribution separately in bins

Belle preliminary



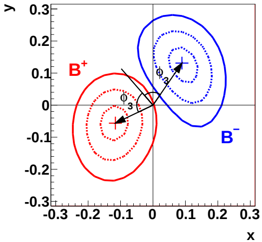
$B^\pm \to DK^\pm$ sample

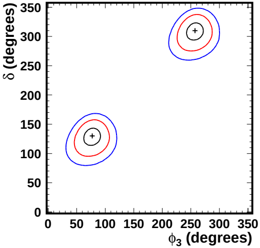
$B^\pm \to D\pi^\pm$ control sample

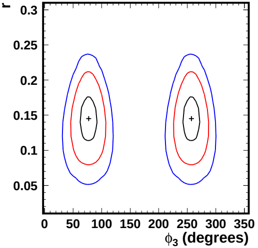
Significant direct CP asymmetry in $B^\pm \to DK^\pm$ sample: probability of stat. fluctuation $p = 0.4\%$.

Simultaneous fit to signal selection variables in all bins. Belle preliminary

Free parameters: (x, y), normalization, background fractions in bins.







$x_- = +0.095 \pm 0.045 \pm 0.014 \pm 0.017$

$y_- = +0.137^{+0.053}_{-0.057} \pm 0.019 \pm 0.029$

$\mathrm{corr}(x_-, y_-) = -0.315$

$x_+ = -0.110 \pm 0.043 \pm 0.014 \pm 0.016$

$y_+ = -0.050^{+0.052}_{-0.055} \pm 0.011 \pm 0.021$

$\mathrm{corr}(x_+, y_+) = +0.059$

$\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.2 \pm 4.3)^\circ$

$r_B = 0.145 \pm 0.030 \pm 0.011 \pm 0.011$

$\delta_B = (129.9 \pm 15.0 \pm 3.9 \pm 4.7)^\circ$

1st error is statistical, 2nd — systematic, 3rd — c_i, s_i precision.

This analysis was done in close communication with CLEO

I think, this is the beginning of a beautiful friendship.

Summary

Two new preliminary Belle results on UT angles with full statistics ($711\ \text{fb}^{-1}$)

- $\sin 2\phi_1$ measurement in "golden modes"
  $B \to J/\psi K^0_S$, $B \to J/\psi K^0_L$, $B \to \psi(2S) K^0_S$, $B \to \chi_{c1} K^0_S$
  $\sin 2\phi_1 = 0.668 \pm 0.023 \pm 0.013$
  Now the most precise measurement of this quantity.
- First ϕ_3 measurement with binned Dalitz plot analysis of $B^\pm \to DK^\pm$, $D \to K^0_S \pi^+ \pi^-$.
  $\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.2(syst) \pm 4.3(c,s))^\circ$
  Precision comparable to model-dependent analysis
  First try of novel procedure to be used at LHCb and Super B factories.

More Belle results with full sample to come soon.
(When life in KEK is back to normal)

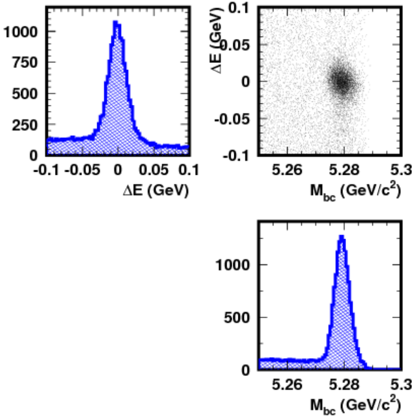
Backup

Signal selection

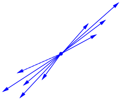
In $\Upsilon(4S)$ decays, pairs of B mesons are produced near threshold.
$E_B = E_{\mathrm{CM}}/2$, small CM momentum (300 MeV$/c$).

Selection variables:

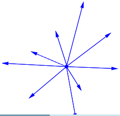
- CM energy difference
  $\Delta E = \sum E_i - E_{\mathrm{CM}}/2$
- B-meson beam-constrained mass
  $M_{\mathrm{bc}} = \sqrt{(E_{\mathrm{CM}}/2)^2 - (\sum p_i)^2}$
- Event shape variables:



$e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$:



$e^+e^- \to b\bar{b}$:



ϕ_3: Flavor-tagged $D^* \to D\pi$, $\overline{D}^0 \to K^0_S\pi^+\pi^-$

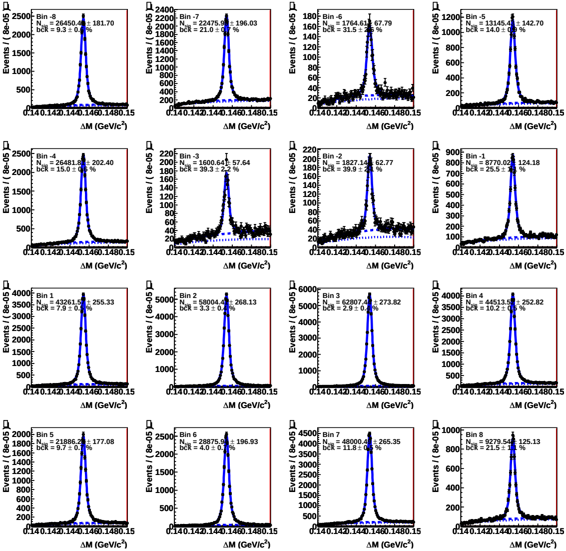
Use momentum range $1.8 < p_D < 2.8$ GeV$/c$ to cancel efficiency shape difference with $B^\pm \to DK^\pm$ (with $p_D \simeq 2.3$ GeV$/c$)

2D fit in $(M_D, \Delta M)$ in each bin.

426900 ± 800 events

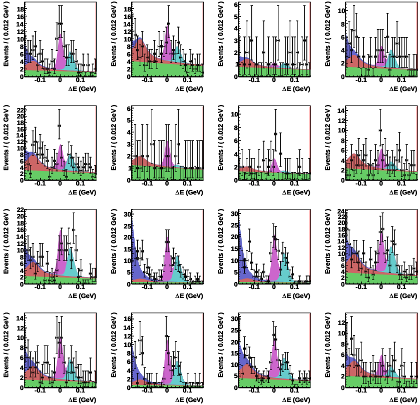
$10.1 \pm 0.5\%$ background

ΔM projections in bins

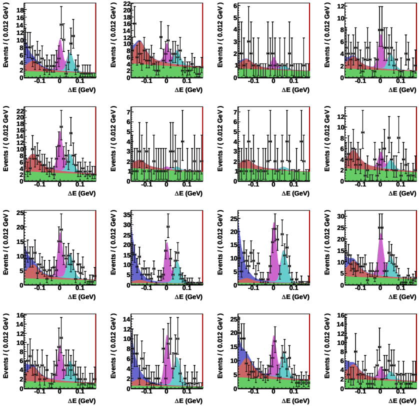


ϕ_3: $B^\pm \to DK^\pm$ fit in bins

ΔE distributions in bins:



$B^- \to DK^-$



$B^+ \to DK^+$

ϕ_3: Systematic errors

Systematic errors in units 10^{-3}.

Source of uncertainty	Δx_-	Δy_-	Δx_+	Δy_+
Dalitz plot efficiency	4.8	2.0	5.6	2.1
Crossfeed between bins	0.4	9.0	0.6	3.0
Signal shape	7.3	7.4	7.3	5.1
u, d, s, c continuum background	6.7	5.6	6.6	3.2
$B\overline{B}$ background	7.8	12.2	7.2	6.1
$B^{\pm} \to D\pi^{\pm}$ background	1.2	4.2	1.9	1.9
Flavor-tagged statistics	1.5	2.7	1.7	1.9
Fit bias	3.2	5.8	3.2	5.8
c_i, s_i precision	10.1	22.5	7.2	17.4
Total without c_i,s_i precision	$\pm$14.0	$\pm$19.4	$\pm$14.0	$\pm$11.3
Total	$\pm$17.3	$\pm$29.7	$\pm$15.7	$\pm$20.7