CPV in B decays at Belle

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Outline

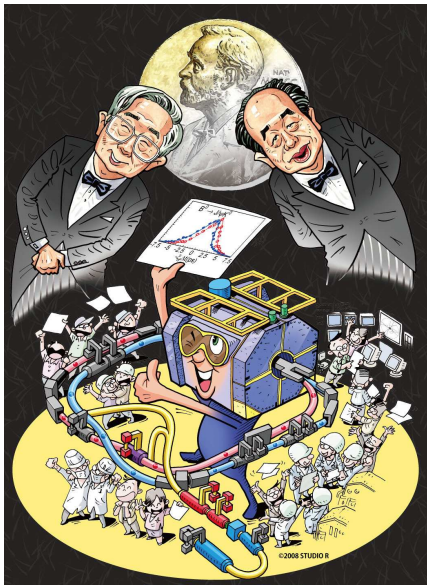
1. **Belle and KEKB**
   - End of operation
   - Luminosity
2. **Experimental results for CPV at Belle**
   - Angles of Unitarity Triangle
   - New Physics Search in CP Violation
3. **Summary**

Outline

End of operation

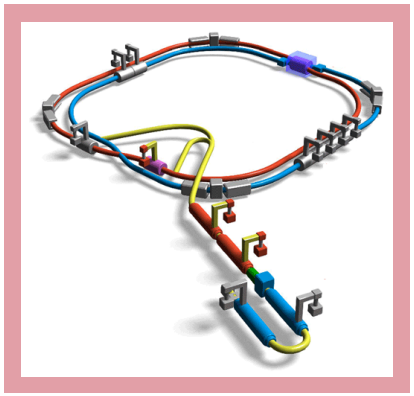
The operation of Belle and KEKB has ended *with great success* (on June 30, 2010)

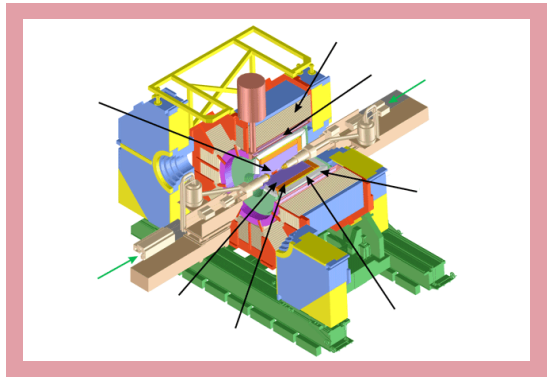
KEKB control room

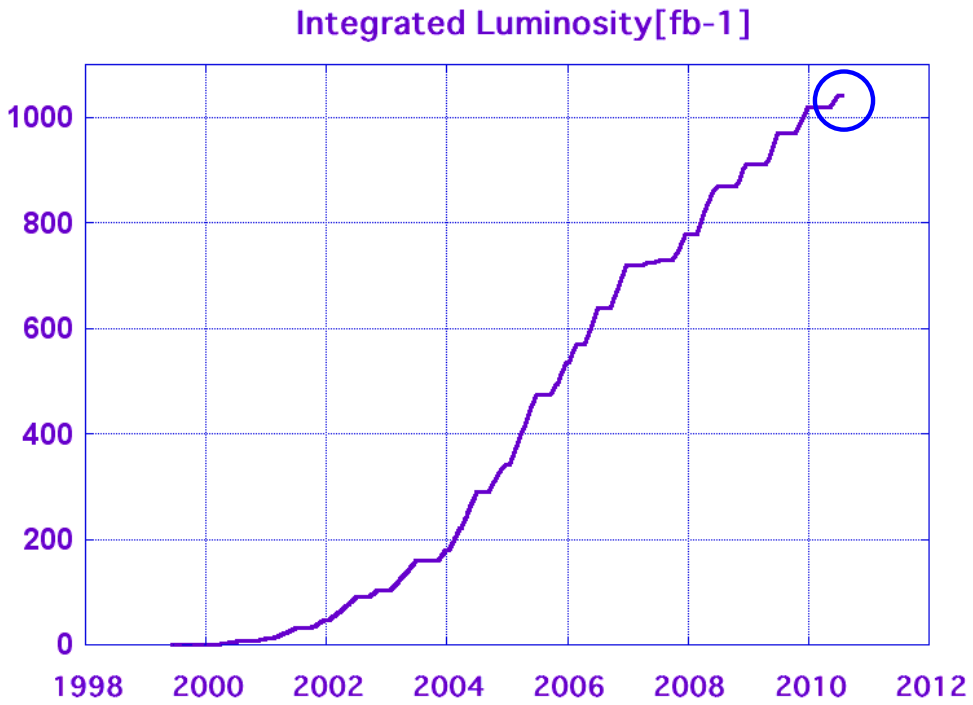


- Upgrades to Belle II and Super KEKB have already started
- Analysis is ongoing in parallel using the full data in Belle ..

Luminosity







Total: $\sim 1020\,\mathrm{fb}^{-1}$

Peak: $2.11 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

On resonance:

$\Upsilon(5S)$: $121\,\mathrm{fb}^{-1}$
$\Upsilon(4S)$: $711\,\mathrm{fb}^{-1}$
$\Upsilon(3S)$: $3\,\mathrm{fb}^{-1}$
$\Upsilon(2S)$: $24\,\mathrm{fb}^{-1}$
$\Upsilon(1S)$: $6\,\mathrm{fb}^{-1}$

Off resonance, scan:

$\sim 100\,\mathrm{fb}^{-1}$

Outline

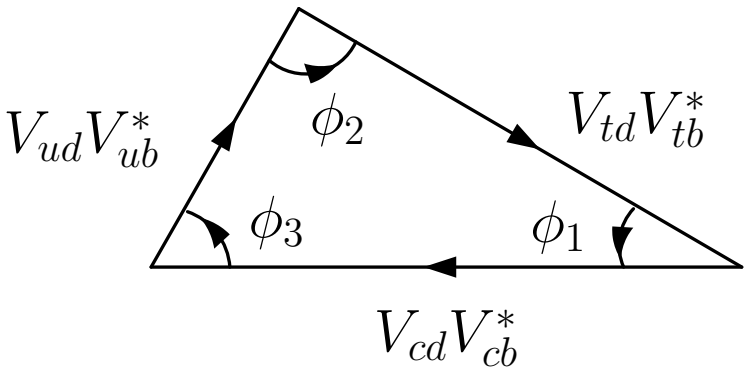
Unitarity Triangle

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

Weak eigenstates — *CKM matrix* — *Mass eigenstates*

- A triangle can be drawn using an unitarity condition of the CKM matrix ;

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



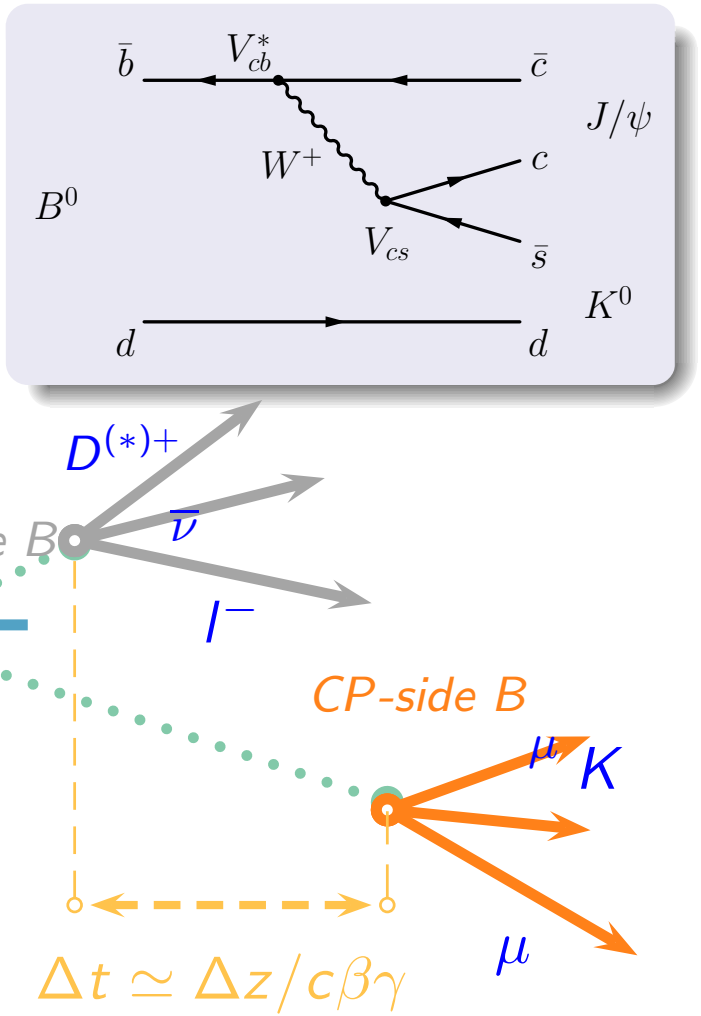
Precise measurements of these angles are the search for New Physics as well as the test of the Standard Model

- may reveal a new source of the *CP* violation

- Golden mode: $B^0 \to J/\psi K^0$
- Contribution from the penguin diagram is negligible
- Time-dependent asymmetry is:

$$\frac{\Gamma(\overline{B}^0(\Delta t)\to f_{CP})-\Gamma(B^0(\Delta t)\to f_{CP})}{\Gamma(\overline{B}^0(\Delta t)\to f_{CP})+\Gamma(B^0(\Delta t)\to f_{CP})} = \mathcal{S}_{CP}\sin(\Delta m\Delta t) + \mathcal{A}_{CP}\cos(\Delta m\Delta t)$$

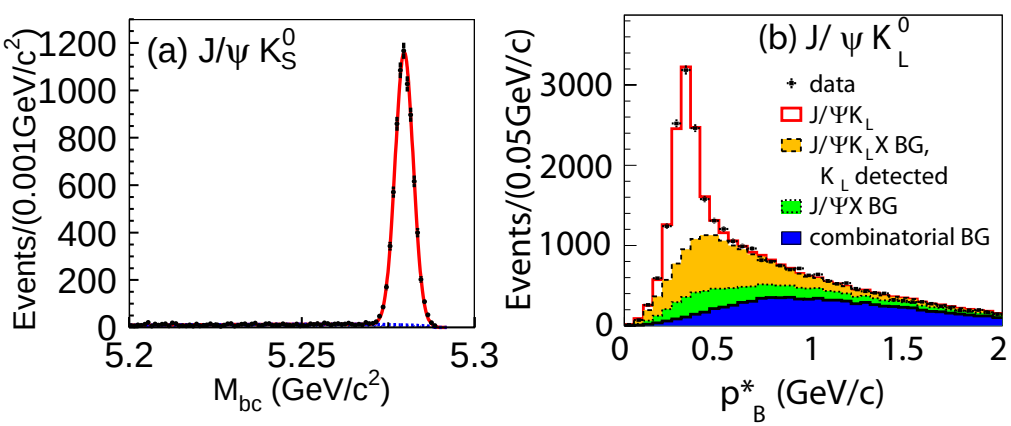
$$\begin{cases} \mathcal{S}_{CP} = -\xi \sin(2\phi_1) \\ \mathcal{A}_{CP} = 0 \end{cases}$$

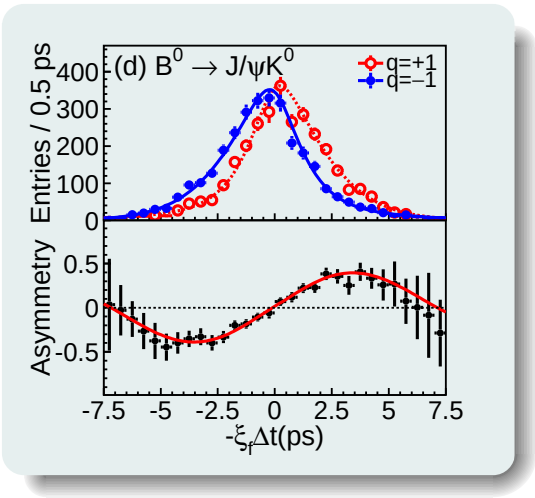


- The flavor of the accompanying B is determined from the flavor information of the final state particles

ϕ_1 from $B^0 \to J/\psi K^0$

- 535M $B\overline{B}$ [PRD 98, 031802 (2007)]: $\begin{cases} N_{\rm sig} = 7,484 \pm 87 \\ N_{\rm sig} = 6,382 \pm 123 \end{cases}$ for $\begin{cases} B^0 \to J/\psi K_S \\ B^0 \to J/\psi K_L \end{cases}$





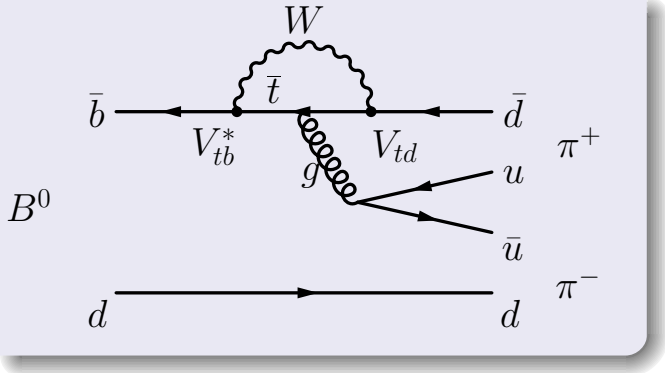
$\sin(2\phi_1) = 0.642 \pm 0.031 \pm 0.017$ ($B^0 \to J/\psi K_S$, $J/\psi K_L$ combined)

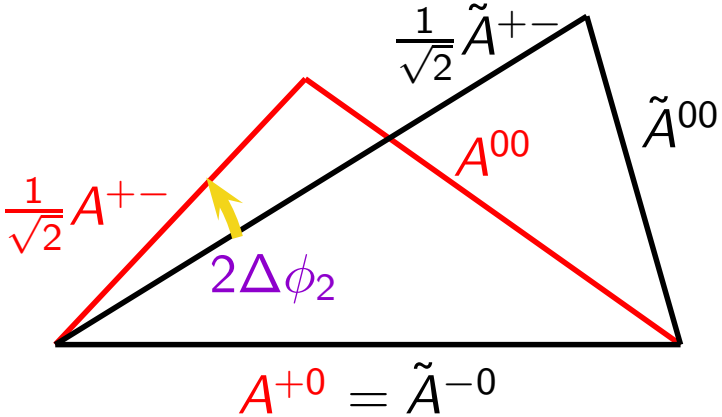
$\hookrightarrow$ will be soon updated with the full data (772M $B\overline{B}$)

- All $c\overline{c}$ resonances will be included with the reprocessed data (high eff.)
- Expected stat. error on $\sin(2\phi_1) \sim 0.02$
- *The size of stat. error on ϕ_1 is approaching to that of syst. error*

ϕ_2

- $\mathcal{S}_{CP} = \sin(2\phi_2)$, $\mathcal{A}_{CP} = 0$ with the tree diagram (T) only
- $\mathcal{A}_{CP} \neq 0$ is possible due to a large penguin contribution $\sim$ T
- An SU(2) isospin analysis is used to extract ϕ_2 from $\phi_2^{\rm eff}$





	Amplitude for
A^{+-} $(\overline{A}^{-+})$	$B^0(\overline{B}^0) \to \pi^+\pi^-$
A^{00} $(\overline{A}^{00})$	$B^0(\overline{B}^0) \to \pi^0\pi^0$
A^{+0} $(\overline{A}^{-0})$	$B^+(B^-) \to \pi^{+(-)}\pi^0$

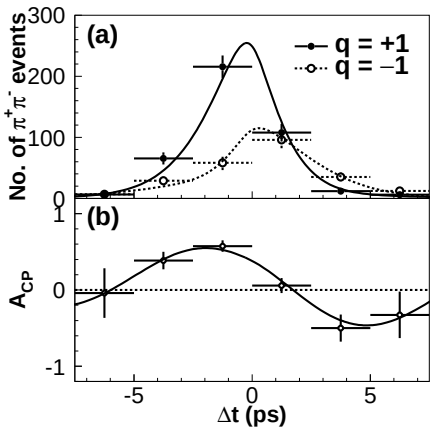
$\tilde{A}^{ij} = e^{2\phi_3}\overline{A}^{ij}$

$$\mathcal{S}_{CP} = \sqrt{1-\mathcal{A}_{CP}^2}\sin(2\phi_2 - 2\Delta\phi_2)$$
$$= \sqrt{1-\mathcal{A}_{CP}^2}\sin(2\phi_2^{\rm eff})$$

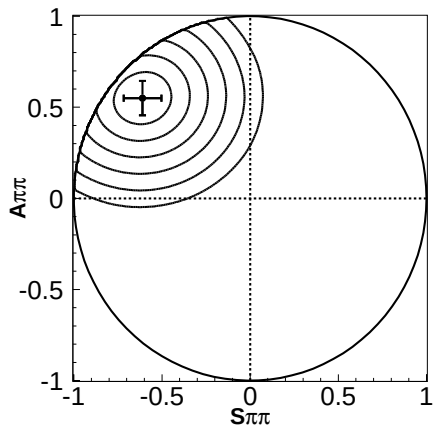
$\mathcal{B}(B^0 \to \pi^+\pi^-)$, $\mathcal{B}(B^0 \to \pi^0\pi^0)$, $\mathcal{B}(B^+ \to \pi^+\pi^0)$, $\mathcal{A}_{CP}(\pi^+\pi^-)$, $\mathcal{S}_{CP}(\pi^+\pi^-)$, $\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0)$ are used for the determination of ϕ_2

ϕ_2 from $B^0 \to \pi\pi$

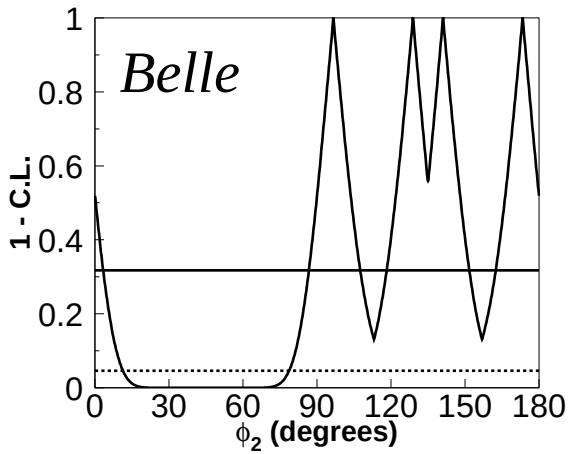
- ϕ_2 measurement using $B^0 \to \pi\pi$ 535M $B\overline{B}$ [PRL 98, 211801 (2007)] : $N_{\rm sig} = 1,464 \pm 65$



(a) Δt and $\mathcal{A}_{CP}$



(b) Confidence regions for $\mathcal{S}_{CP}$ and $\mathcal{A}_{CP}$



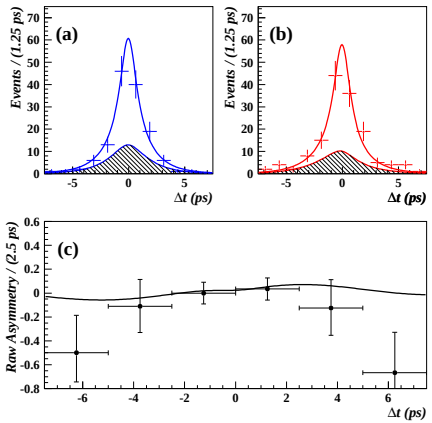
(c) 1-C.L.

- (a) The difference in the heights of B-flavors is due to direct CP violation
- (b) $\mathcal{A}_{CP} = +0.55 \pm 0.08 \pm 0.05\,(5.5\sigma)$, $\mathcal{S}_{CP} = +0.61 \pm 0.10 \pm 0.04\,(5.3\sigma)$
- (c) Scan ϕ_2 and construct χ^2 for the five amplitudes (A^{+0}, A^{+-}, A^{00}, $\tilde{A}^{+-}$, $\tilde{A}^{00}$): WA are used for $\mathcal{B}(\pi\pi)$s, $\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0)$

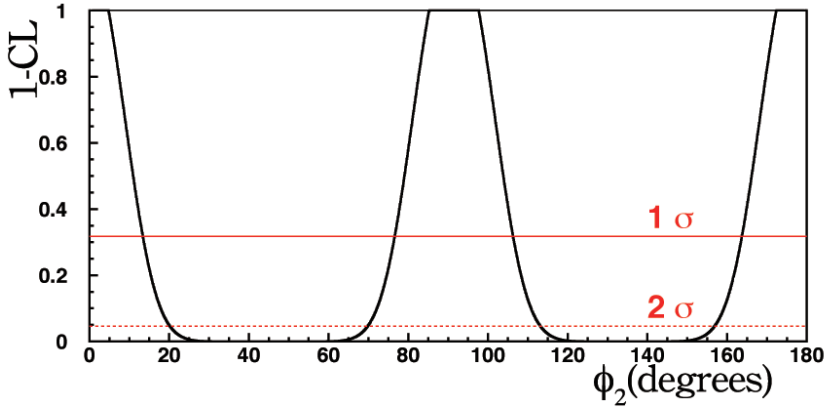
$\phi_2 = (97 \pm 11)^\circ$: exclude $[11^\circ, 79^\circ]$ at 95% CL

ϕ_2 from $B^0 \to \rho\rho$

- ϕ_2 measurement using $B^0 \to \rho\rho$ 535M $B\overline{B}$ [PRD 76, 011104 (2007)] : $N_{\rm sig} = 576 \pm 53$
- Best environment for constraining ϕ_2 because of relatively small penguins
- Assuming 100% longitudinally polarized (∼pure *CP*-even state)
- Isospin analysis : Use Belle results for $\mathcal{B}(B^0 \to \rho^0\rho^0)$ ($< 1.0 \times 10^{-6}$ at 90% CL) in 2008, otherwise WA
  - before BaBar's $\mathcal{B}(\rho^+\rho^0)$ update



(a) Δt and $\mathcal{A}_{CP}$



(b) 1-C.L.

PRD 78, 111102(R) (2008)

$$\phi_2 = (91.7 \pm 14.9)^\circ$$

ϕ_2 from $B^0 \to \rho\pi$

- ϕ_2 measurement using $B^0 \to \rho\pi$ 449M $B\overline{B}$ [PRL 98, 221602 (2007)] : $N_{\rm sig} = 971 \pm 42$
- Dalitz plot-dependent differential decay rate is:

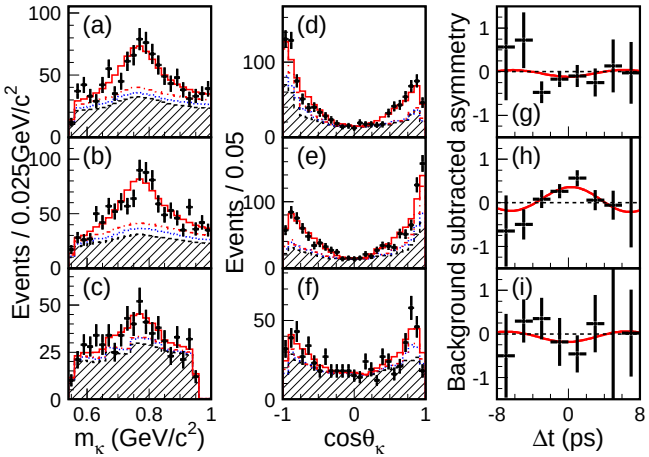
$$\frac{d\Gamma}{d\Delta t ds_+ ds_-} \sim e^{-|\Delta t|/\tau_{B^0}} \left\{ (|A_{3\pi}|^2 + |\overline{A}_{3\pi}|^2) - q_{\rm tag}(|A_{3\pi}|^2 - |\overline{A}_{3\pi}|^2)\cos(\Delta m_d \Delta t) \right.$$
$$\left. + q_{\rm tag} 2{\rm Im}\left[\frac{q}{p} A^*_{3\pi}\overline{A}_{3\pi}\right]\sin(\Delta m_d \Delta t) \right\}$$

where $A_{3\pi}$ is the Dalitz plot-dependent complex amplitudes for $B^0(\overline{B}^0) \to \rho^+\pi^-, \rho^-\pi^+, \rho^0\pi^0$, with dynamical properties.

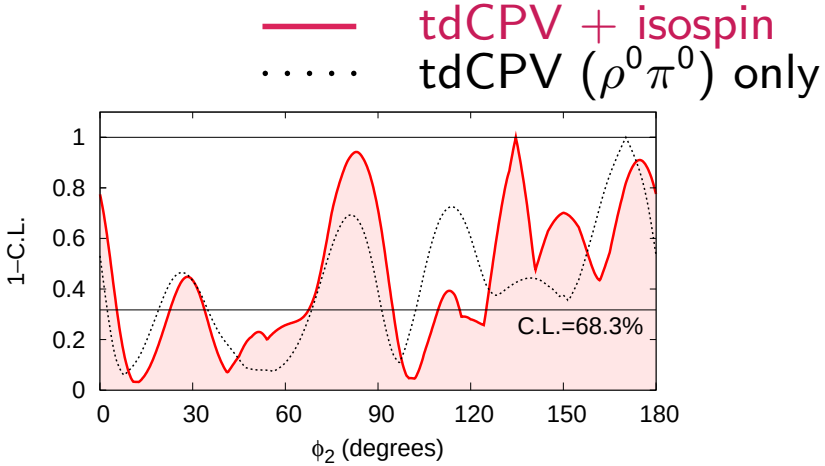
$\rho^+\pi^-$

$\rho^-\pi^+$

$\rho^0\pi^0$



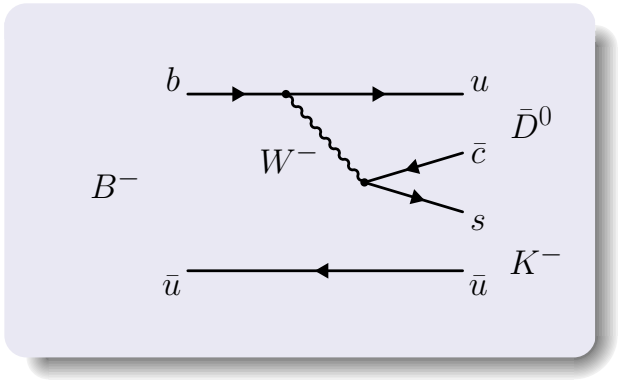
(a) mass, helicity and Δt



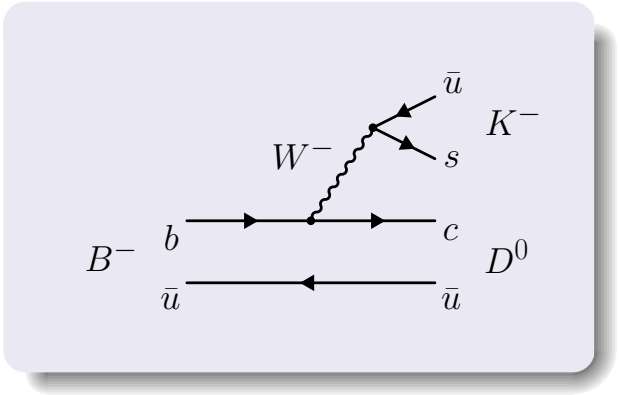
(b) 1-C.L.

$68^\circ < \phi_2 < 95^\circ$ at 68.3% CL

ϕ_3 from $B^+ \to DK^+$ (GGSZ)



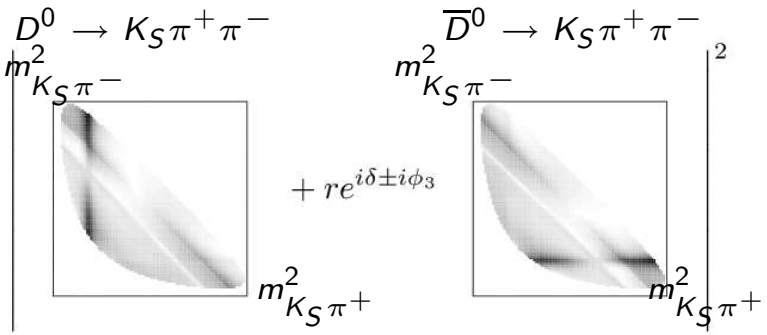
$B^- \to \overline{D}^0 K^-$



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

- Amplitude ratio $(r_B) \approx \frac{|V_{ub}^* V_{cs}|}{|V_{cb}^* V_{us}|} \times$ color sup. ~ 0.1
- For the same final state of D^0 and $\overline{D}^0$ decays:
  $|\tilde{D}^0\rangle = r_B e^{i\theta} |\overline{D}^0\rangle + |D^0\rangle$ $(\theta = -\phi_3 + \underline{\delta_B}$; strong phase difference)
- D can be distinguished as $D^0/\overline{D}^0$ on the Dalitz plane

$$|A(m^2_{K_S\pi^+}, m^2_{K_S\pi^-})|^2 =$$



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

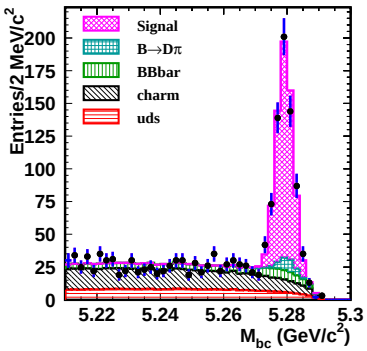
ϕ_3 from $B^+ \to DK^+$ (GGSZ)

- Fit $x_\pm = r_B \cos(\delta_B \pm \phi_3)$, $y_\pm = r_B \sin(\delta_B \pm \phi_3)$ with a Dalitz plot model of D decay and other kinematical variables
- Model of D decay is determined using $D^{*+} \to D^0\pi^+$, then used for the CP fit $\to$ large model uncertainty for ϕ_3
- model-independent approach is now tested using CLEO-c data
  [A. Bondar, A. Poluektov, Eur. Phys. J. C 47, 347 (2006) and C 55, 51 (2008)]

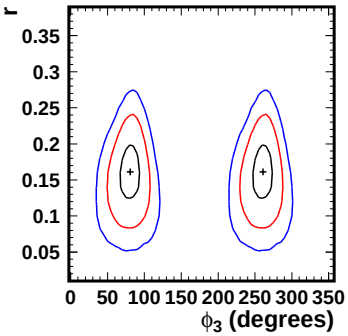
- 657M $B\overline{B}$ [PRD 81, 112002 (2010)]
  model-dependent approach
  (Plots of $B^+ \to DK^+$ are shown here)

	$N_{\rm sig}$
$B^+ \to DK^+$	756
D^*K, $D^{*0} \to D\pi^0$	149
D^*K, $D^{*0} \to D\gamma$	141

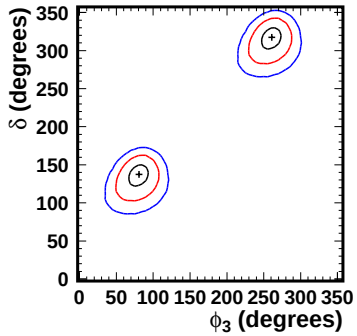
Evidence for direct CPV (3.5σ)



(a) mass



(b) CL (r_B, ϕ_3)



(c) CL (δ_B, ϕ_3)

$\phi_3 = 78.4^\circ {}^{+10.8^\circ}_{-11.6^\circ} \pm 3.6^\circ(\text{syst}) \pm 8.9^\circ(\text{model})$ (all modes combined)

ϕ_3 from $B^+ \to DK^+$ (ADS)

- New result from Belle for ADS mode
- $B^+ \to DK^+$ $(D \to K^-\pi^+)$ where $D = D^0$ or $\overline{D}^0$

$$\begin{cases} B^+ \to D^0 K^+ & D^0 \to K^-\pi^+ \\ B^+ \to \overline{D}^0 K^+ & \overline{D}^0 \to K^-\pi^+ \end{cases}$$

  Either B or D decay is suppressed

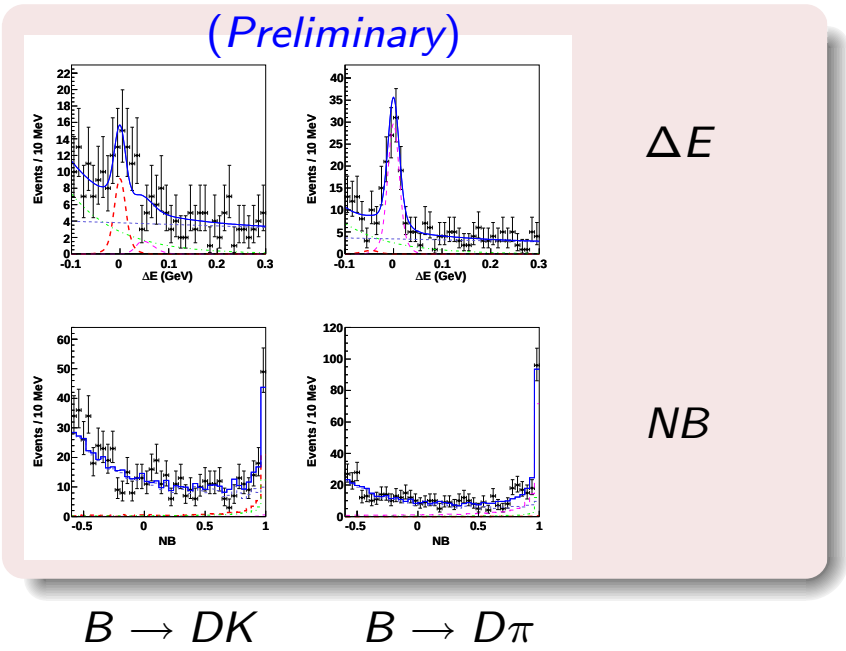
- CP asymmetry and partial rate are the key for ϕ_3 extraction :

$$\begin{aligned} \mathcal{A}_{Dh} &\equiv \frac{\mathcal{B}(B^- \to [K^+\pi^-]_D h^-) - \mathcal{B}(B^+ \to [K^-\pi^+]_D h^+)}{\mathcal{B}(B^- \to [K^+\pi^-]_D h^-) + \mathcal{B}(B^+ \to [K^-\pi^+]_D h^+)} \\ &= 2 r_B r_D \sin(\delta_B + \delta_D) \sin(\phi_3)/\mathcal{R}_{Dh} \\ \mathcal{R}_{Dh} &\equiv \frac{\mathcal{B}(B^- \to [K^+\pi^-]_D h^-) + \mathcal{B}(B^+ \to [K^-\pi^+]_D h^+)}{\mathcal{B}(B^- \to [K^-\pi^+]_D h^-) + \mathcal{B}(B^+ \to [K^+\pi^-]_D h^+)} \\ &= r_B^2 r_D^2 2 r_B r_D \cos(\delta_B + \delta_D) \cos(\phi_3) \end{aligned}$$

[D. Atwood, I. Dunietz and A. Soni, PRL 78, 3357 (1997)]

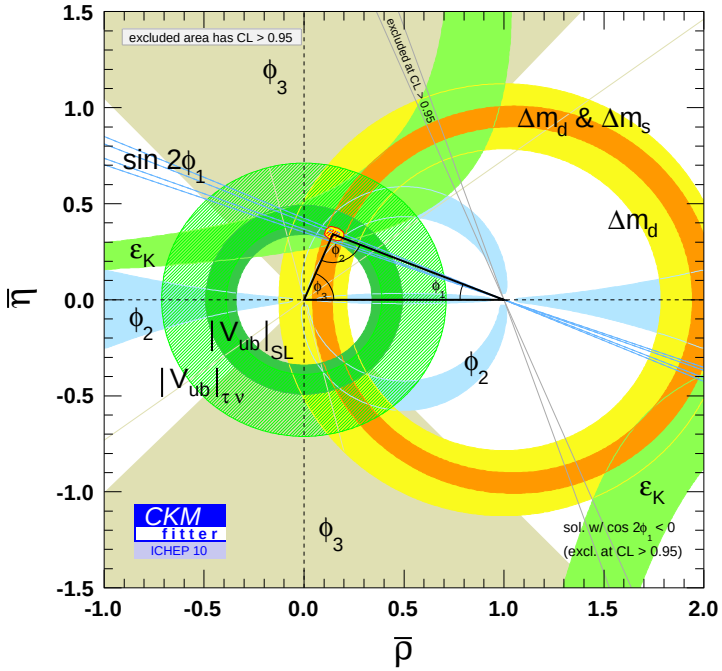
ϕ_3 from $B^+ \to DK^+$ (ADS)

- First evidence of ADS $B^+ \to DK^+$ signal with a significance of 3.8σ with 772M $B\overline{B}$ (full data in Belle)
  $\mathcal{A}_{DK} = -0.39 \pm 0.26(\text{stat})^{+0.06}_{-0.04}(\text{syst})$
  $\mathcal{R}_{DK} = [1.62 \pm 0.42(\text{stat})^{0.16}_{-0.19}(\text{syst})] \times 10^{-2}$
- Discrimination between signal and background is improved using NeuroBayes (NB), a technique for multi-variate analysis
- 2D fit is performed using $\Delta E \equiv E_B - E_{\text{beam}}$, and NB

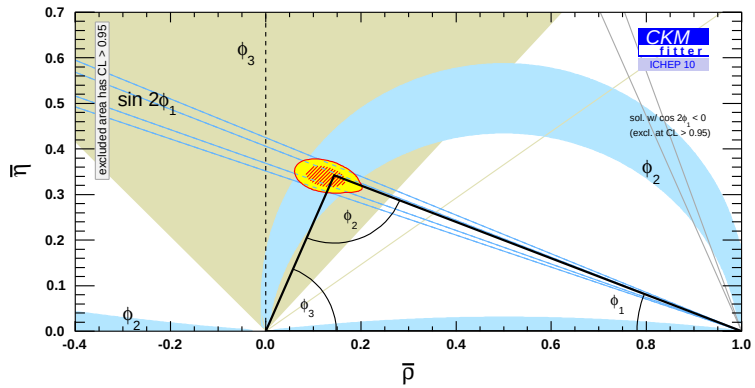


- External information will be used to constrain ϕ_3:
  r_D and δ_D may come from HFAG and CLEO-c

Constraints on Unitarity Triangle so far



(a) CKM fitter: full inputs



(b) CKM fitter: angles only

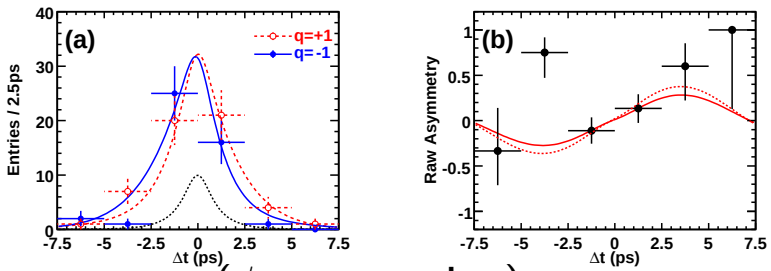
- No discrepancy from SM, still in consistency

New Physics Search in CP Violation

New physics search by $\phi_1^{\rm eff}$ measurements in $b \to sq\overline{q}$ modes

- deviation from $b \to c\overline{c}s$ indicates the physics beyond SM (prediction: $\delta \sin(2\phi_1) \sim \mathcal{O}(\%)$)

- New result from Belle for $B \to K_S K^+ K^-$
  657M $B\overline{B}$ [PRD 82, 073011 (2010)]
- Time-dependent Dalitz-plot analysis simultaneously determined $\phi_1^{\rm eff}$ for ϕK_S, $f_0(980) K_S$ and other $K_S K^+ K^-$



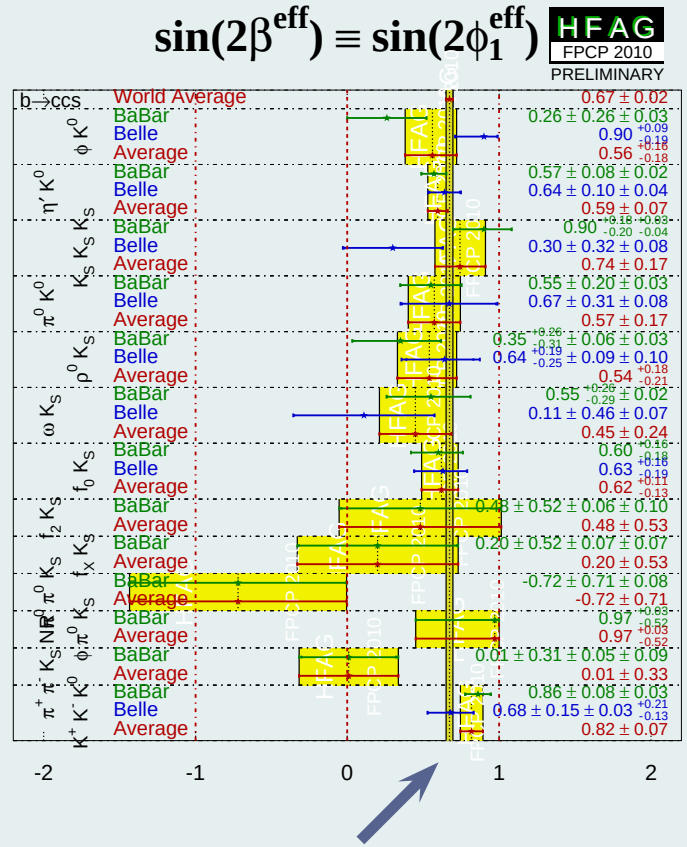
(ϕ mass region)

(a) Δt (b) $\mathcal{A}_{CP}$

- A solution preferred from multiple solutions:

$$\begin{cases} \phi K_S : & \phi_1^{\rm eff} = 32.2 \pm 9.0 \pm 1.4 \\ f_0(980) K_S : & \phi_1^{\rm eff} = 31.3 \pm 9.0 \pm 4.0 \end{cases}$$

Various approaches for $\phi_1^{\rm eff}$ still consistent with SM



$$\phi_1 = (22 \pm 1)^\circ$$

Outline

Summary

Accuracies of CKM angles are improving day by day

- ϕ_1 - Stat. error on ϕ_1 is approching to the syst. error
- ϕ_2 - $B \to \rho\rho$ mode currently gives tightest constraint on ϕ_2, but $B \to \rho\pi$ mode can constrain ϕ_2 without ambiguity
- ϕ_3 - Error on ϕ_3 from the Dalitz plot analysis has started to be saturated by the model error
- New Physics search through the CPV in B decays achieved many results, but still consistent with SM so far

Need to improve stat. errors for further inspection of CPV

- Belle will soon update important analyses with the full data
- Belle II will further extend our knowledge on CPV in near future