CPV measurement in B decays at Belle

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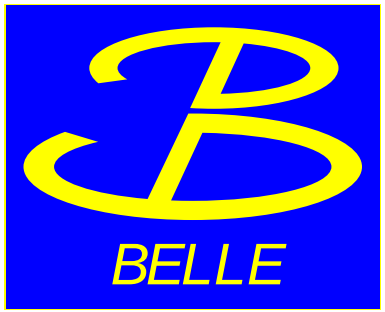
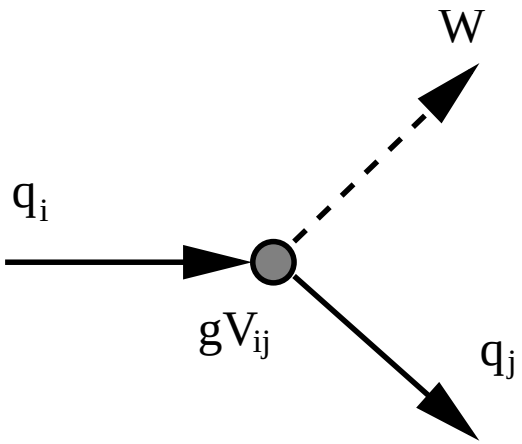
On behalf of Belle collaboration



Unitarity triangle



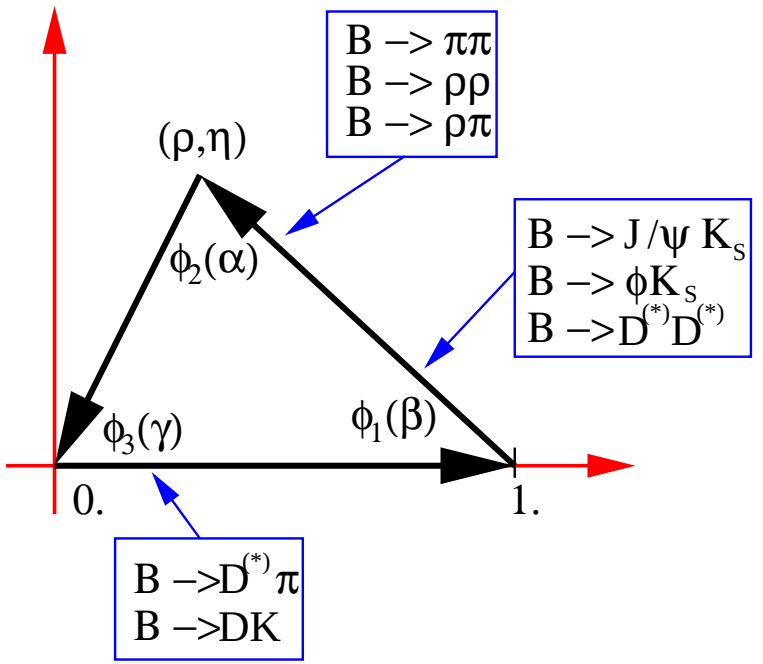
Unitarity: $V_{ij}^* V_{jk} = \delta_{ik}$

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

Wolfenstein parametrization:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$\lambda = 0.2235 \pm 0.0033$



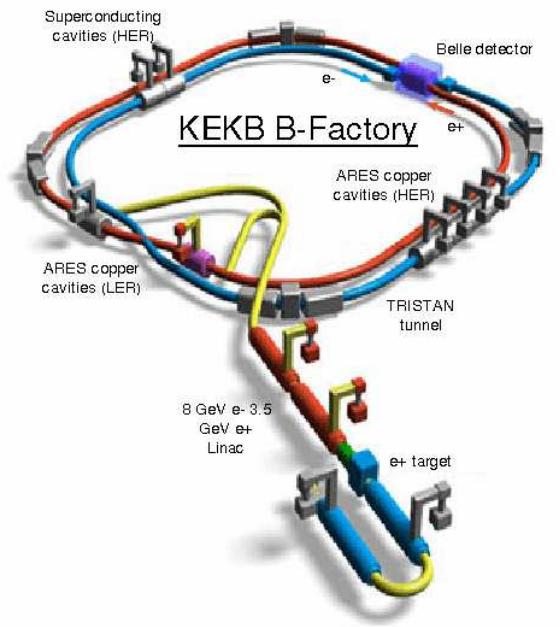
$\phi_1 = 21.1^\circ \pm 0.9^\circ$

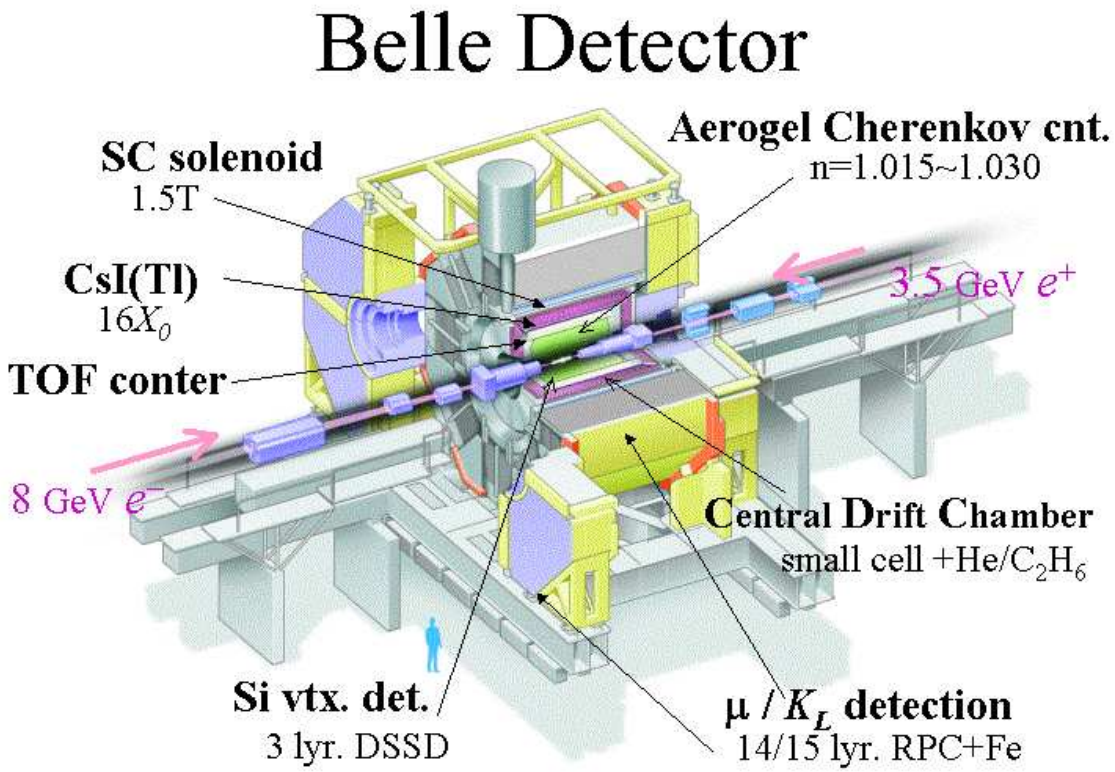
$\phi_2 = 89^\circ \pm 4^\circ$ [CKMfitter]

$\phi_3 = 70^\circ {}^{+27^\circ}_{-30^\circ}$

This talk: Updated ϕ_3 measurement with $B \to DK$ Dalitz analysis

Belle experiment

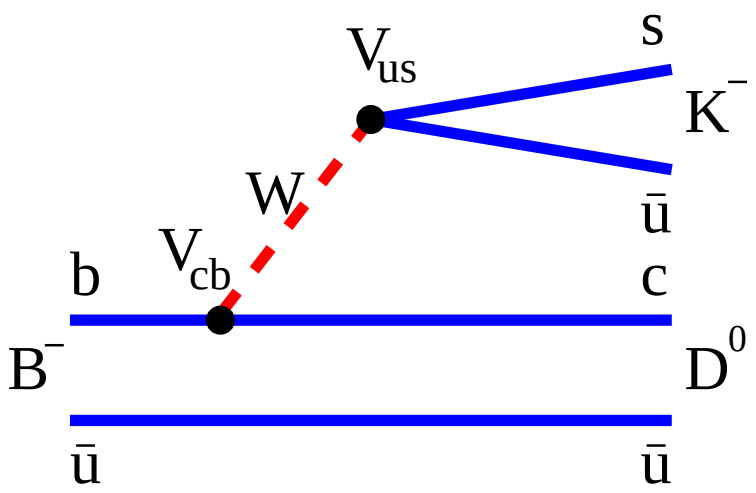




- Belle detector, KEKB collider at KEK laboratory, Tsukuba, Japan
- World record luminosity: $L \simeq 2.1 \times 10^{34}$ cm^{-2}s^{-1} (at $\Upsilon(5S)$).
- Accumulated samples:
  - 710 fb^{-1} at $\Upsilon(4S)$ (772×10^6 $B\overline{B}$ decays)
  - 105 fb^{-1} at $\Upsilon(5S)$
  - $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, energy scans

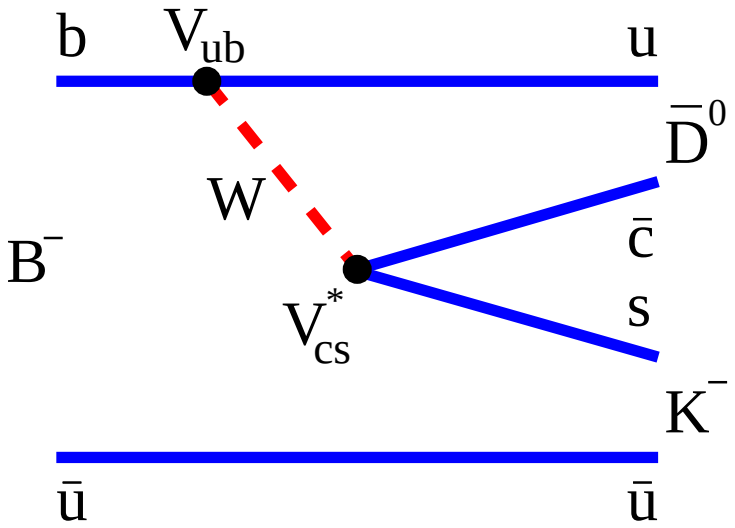
Measurement of ϕ_3 in $B \to DK$ decays

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



+

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



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

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

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 $\theta = \phi_3 + \delta$ $(B^+ \to DK^+)$, $\theta = -\phi_3 + \delta$ $(B^- \to DK^-)$.

Ratio of the two amplitudes:

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

Dalitz analysis of D decay from $B^{\pm} \to DK^{\pm}$

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

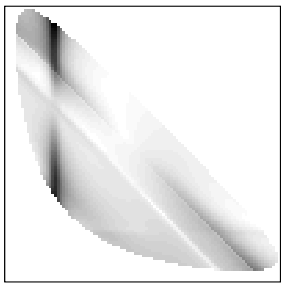
[A. Bondar, Belle Dalitz analysis meeting, 24-26 Sep. 2002]

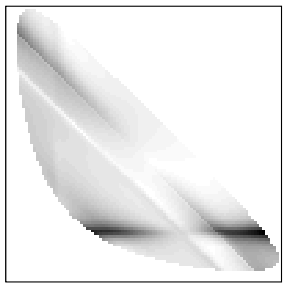
Use $B^{\pm} \to D^{(*)}K^{(*)\pm}$ modes with 3-body decay $D \to K_S\pi^+\pi^-$.

Dalitz plot density: $d\sigma_{\pm}(m_+^2, m_-^2) \sim |M_{\pm}|^2 dm_+^2 dm_-^2$

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

$$= \left| \quad + re^{i\delta_B \pm i\phi_3} \quad \right|^2$$





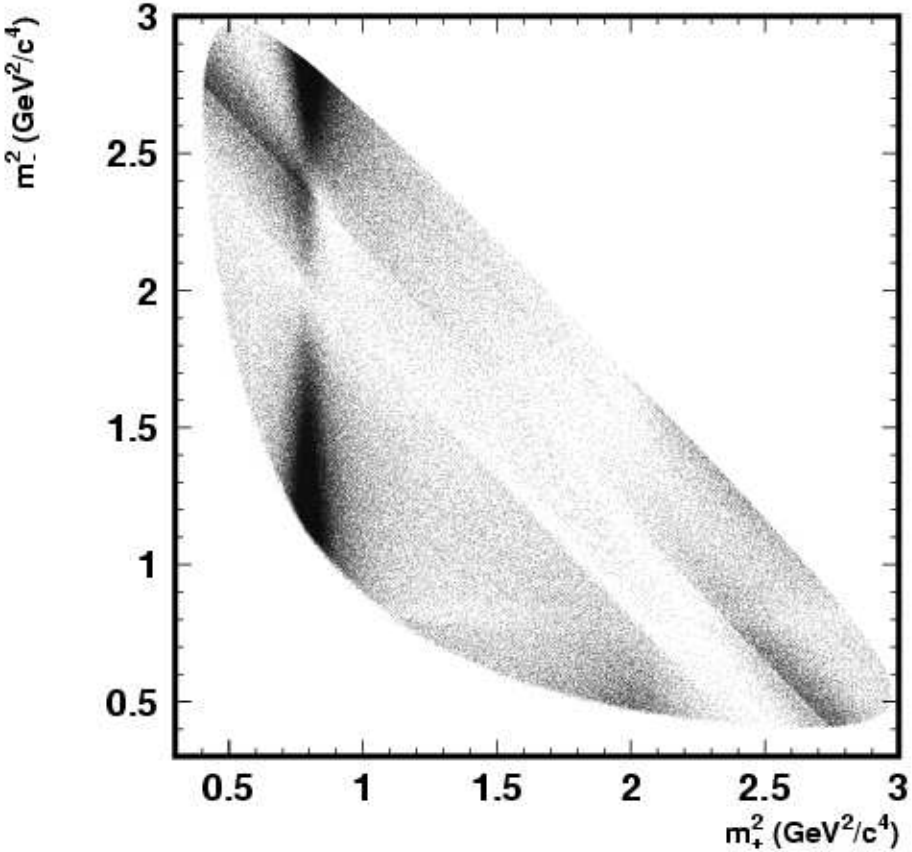
$\overline{D}^0 \to K_S^0\pi^+\pi^-$ amplitude f_D is extracted from continuum ($D^{*\pm} \to D\pi^{\pm}$), parametrized as a set of two-body amplitudes.

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

Fit variables: $x_{\pm} = r\cos(\delta_B \pm \phi_3)$, $y_{\pm} = r\sin(\delta_B \pm \phi_3)$.

$\overline{D}^0 \to K^0_S\pi^+\pi^-$ amplitude

605 fb^{-1} sample. [arXiv:0803.3375]
Extracted from $D^{*\pm} \to D\pi^{\pm}$,
$\overline{D}^0 \to K^0_S\pi^+\pi^-$ process.
Fit with isobar model.



Intermediate state	Amplitude	Phase (°)
$K_S\sigma_1$	1.56 ± 0.06	214 ± 3
$K_S\rho^0$	1.0 (fixed)	0 (fixed)
$K_S\omega$	0.0343 ± 0.0008	112.0 ± 1.3
$K_S f_0(980)$	0.385 ± 0.006	207.3 ± 2.3
$K_S\sigma_2$	0.20 ± 0.02	212 ± 12
$K_S f_2(1270)$	1.44 ± 0.04	342.9 ± 1.7
$K_S f_0(1370)$	1.56 ± 0.12	110 ± 4
$K_S\rho^0(1450)$	0.49 ± 0.08	64 ± 11
$K^*(892)^+\pi^-$	1.638 ± 0.010	133.2 ± 0.4
$K^*(892)^-\pi^+$	0.149 ± 0.004	325.4 ± 1.3
$K^*(1410)^+\pi^-$	0.65 ± 0.05	120 ± 4
$K^*(1410)^-\pi^+$	0.42 ± 0.04	253 ± 5
$K^*_0(1430)^+\pi^-$	2.21 ± 0.04	358.9 ± 1.1
$K^*_0(1430)^-\pi^+$	0.36 ± 0.03	87 ± 4
$K^*_2(1430)^+\pi^-$	0.89 ± 0.03	314.8 ± 1.1
$K^*_2(1430)^-\pi^+$	0.23 ± 0.02	275 ± 6
$K^*(1680)^+\pi^-$	0.88 ± 0.27	82 ± 17
$K^*(1680)^-\pi^+$	2.1 ± 0.2	130 ± 6
non-resonant	2.7 ± 0.3	160 ± 5

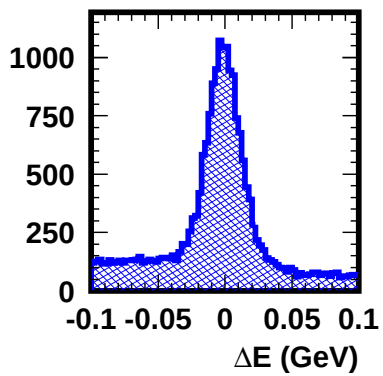
B meson selection

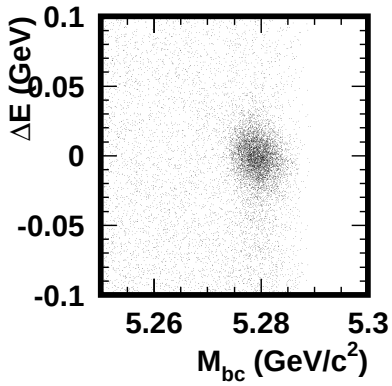
In $\Upsilon(4S)$ decays, pairs of B mesons are produced near threshold.

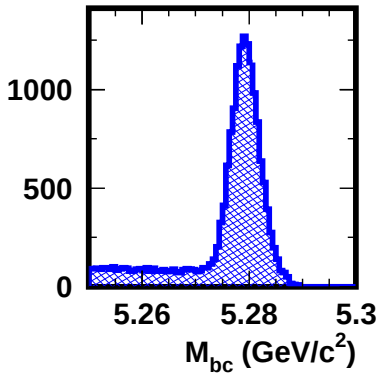
$E_B = E_{\rm CM}/2$, small CM momentum (300 MeV/c).

Selection variables:

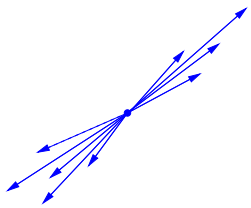
- CM energy difference
  $\Delta E = \sum E_i - E_{\rm CM}/2$
- B-meson beam-constrained mass
  $M_{\rm bc} = \sqrt{(E_{\rm CM}/2)^2 - (\sum p_i)^2}$
- Event shape: thrust angle ($\cos\theta_{\rm thr}$), Fisher discriminant based on "virtual calorimeter" ($\mathcal{F}$).



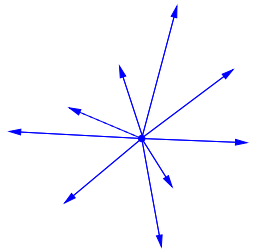




$e^+e^- \to u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$:



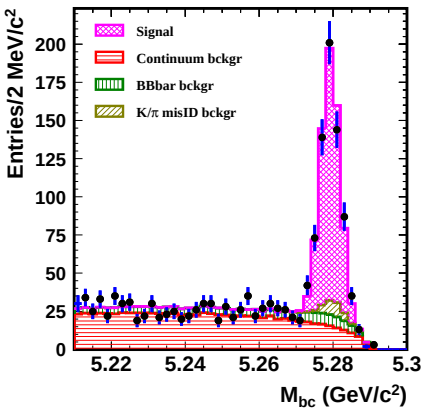
$e^+e^- \to b\bar{b}$:

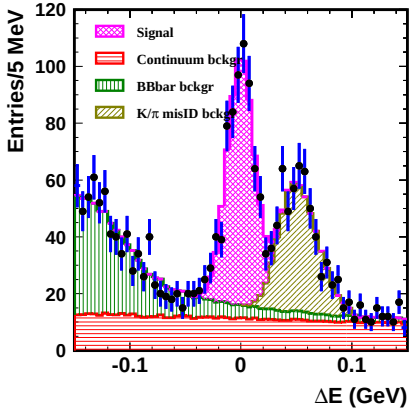


$B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D^{*}K^{\pm}$, $D^{*} \to D\pi^{0}$ modes

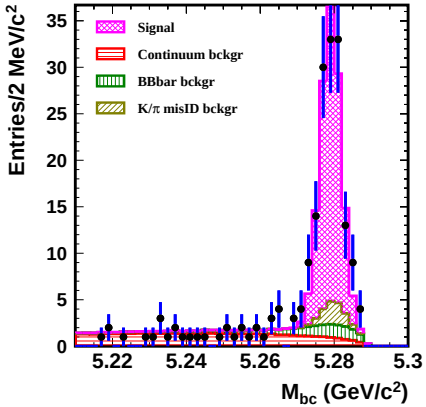
605 fb^{-1} data sample. [arXiv:0803.3375]

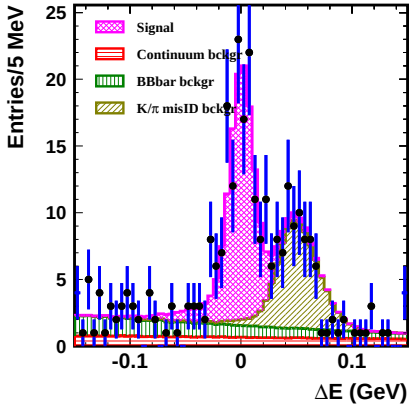
$B^{\pm} \to DK^{\pm}$





$B^{\pm} \to D^{*}K^{\pm}$, $D^{*} \to D\pi^{0}$





Signal selections:

$|M_{K_S\pi\pi} - M_D| < 11$ MeV/c^2

$144.9 < \Delta M < 145.9$ MeV/c^2 (for $B^{\pm} \to D^{*}K^{\pm}$)

$|\Delta E| < 30$ MeV

$M_{\rm bc} > 5.27$ MeV/c^2

$B^{\pm} \to DK^{\pm}$:	756 events, 29% background
$B^{\pm} \to D^{*}(D\pi^{0})K^{\pm}$:	149 events, 20% background

In the "clean" region
$|\cos\theta_{\rm thr}| < 0.8, \mathcal{F} > -0.7$

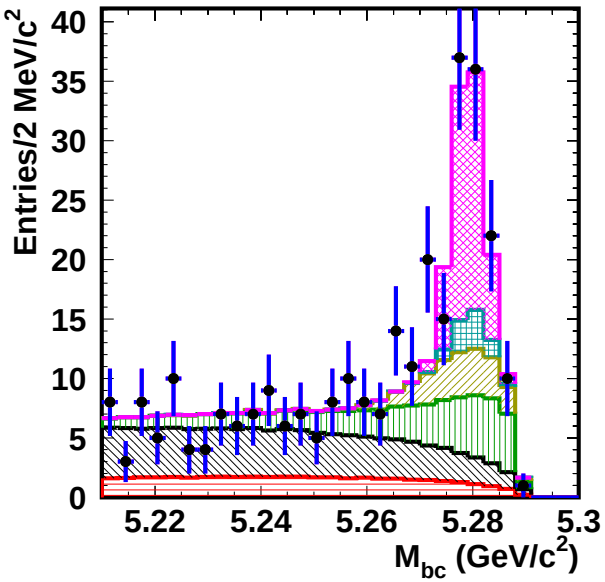
Whole $\cos\theta_{\rm thr}$, $\mathcal{F}$ range used in Dalitz plot fit.

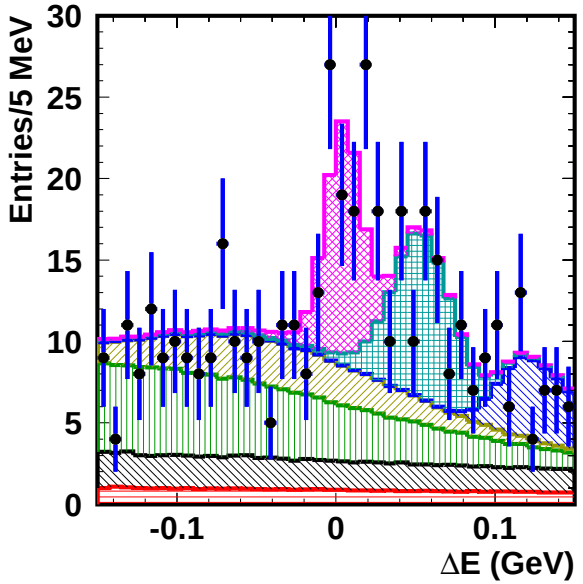
$B^{\pm} \to D^{*}K^{\pm}$, $D^{*} \to D\gamma$ mode

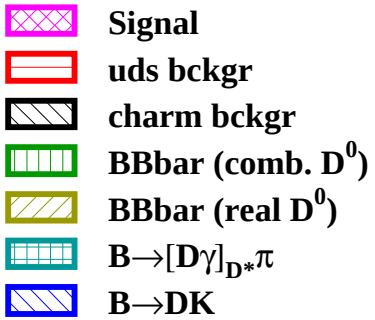
NEW

605 fb^{-1} data sample.

Belle preliminary







Signal selections:

$|M_{K_S\pi\pi} - M_D| < 11$ MeV/c^2

$\Delta M < 152$ MeV/c^2

$E_\gamma > 100$ MeV

141 events, 58% background.

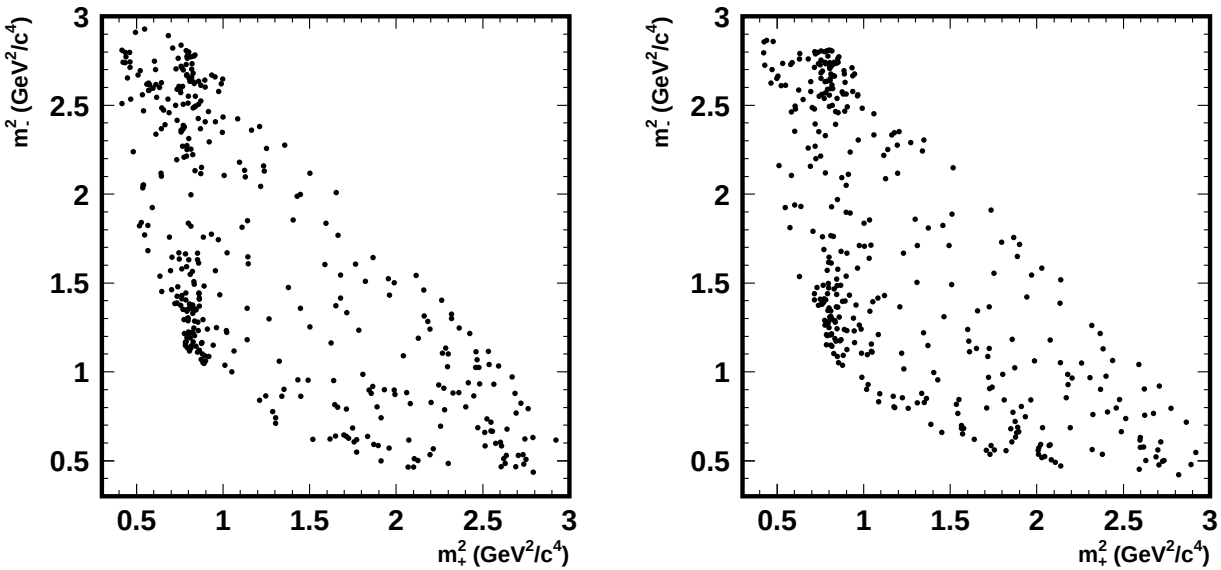
$|\Delta E| < 30$ MeV

$M_{\rm bc} > 5.27$ MeV/c^2

In the "clean" region
$|\cos\theta_{\rm thr}| < 0.8, \mathcal{F} > -0.7$

Dalitz plot fits

$B^+ \to DK^+$ $B^- \to DK^-$



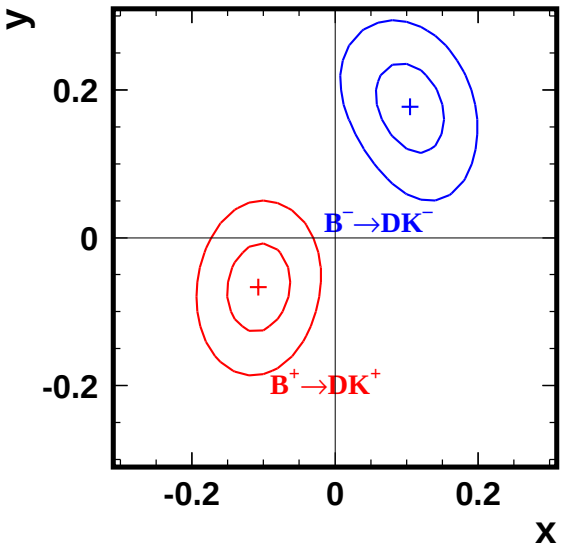
Fit $D \to K^0_S \pi^+ \pi^-$ Dalitz plots separately for B^+ and B^-.
Use $M_{\rm bc}$, ΔE, $\cos\theta_{\rm thr}$, $\mathcal{F}$ in the likelihood (no cut on $\cos\theta_{\rm thr}$ and $\mathcal{F}$).

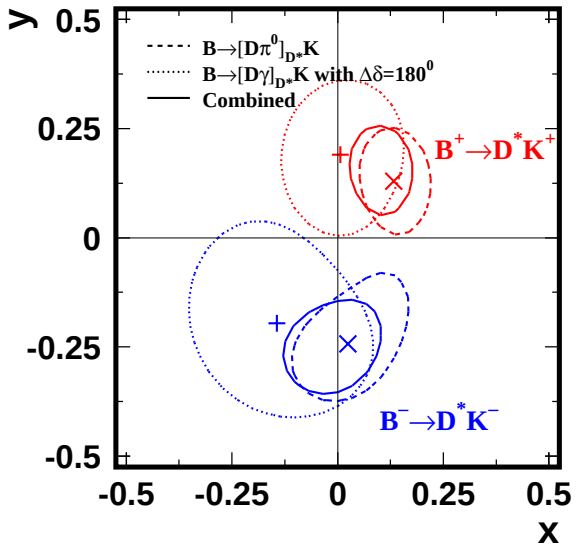
Unbinned likelihood fit: $$-2\log\mathcal{L} = -2\left[\sum_{i=1}^{n}\log p_i - \log\int_D p\right]$$

$$p = \sum_{k=\rm sig,bck} p_k(m_+^2, m_-^2)\, p_k(M_{\rm bc}, \Delta E)\, p_k(\cos\theta_{\rm thr}, \mathcal{F})$$

Dalitz plot fits

Fit variables: $x_\pm = r\cos(\delta_B \pm \phi_3)$, $y_\pm = r\sin(\delta_B \pm \phi_3)$.





← x, y sign swapped for $D^* \to D\gamma$

Strong phase difference 180° for $D^* \to D\pi^0$ and $D^* \to D\gamma$ samples.

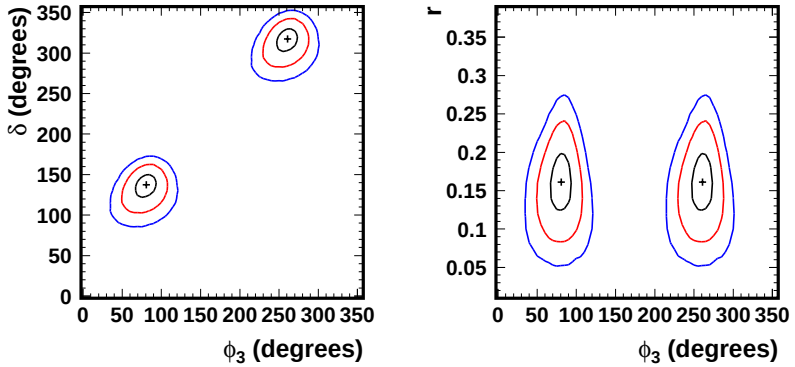
[A. Bondar, T. Gershon, PRD **70**, 091503 (2004)]

	$B^\pm \to DK^\pm$	$B^\pm \to D^*(D\pi^0)K^\pm$	$B^\pm \to D^*(D\gamma)K^\pm$
x_-	$+0.105 \pm 0.047 \pm 0.011$	$+0.024 \pm 0.140 \pm 0.018$	$+0.144 \pm 0.208 \pm 0.025$
y_-	$+0.177 \pm 0.060 \pm 0.018$	$-0.243 \pm 0.137 \pm 0.022$	$+0.196 \pm 0.215 \pm 0.037$
x_+	$-0.107 \pm 0.043 \pm 0.011$	$+0.133 \pm 0.083 \pm 0.018$	$-0.006 \pm 0.147 \pm 0.025$
y_+	$-0.067 \pm 0.059 \pm 0.018$	$+0.130 \pm 0.120 \pm 0.022$	$-0.190 \pm 0.177 \pm 0.037$

Fit results in (ϕ_3, r, δ)

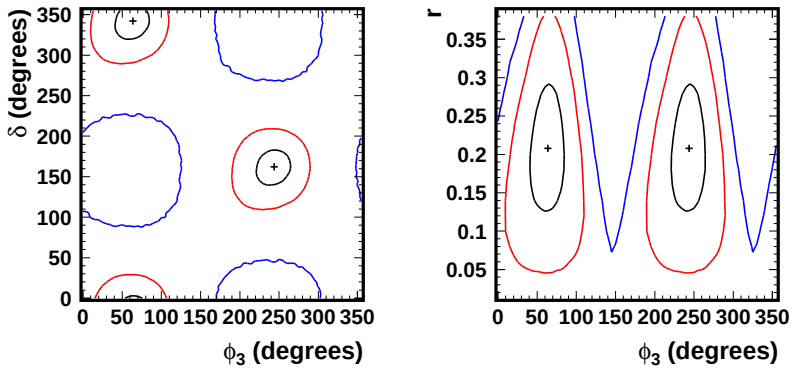
Feldman-Cousins stat. treatment to translate $(x_\pm, y_\pm) \to (r, \phi_3, \delta)$

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



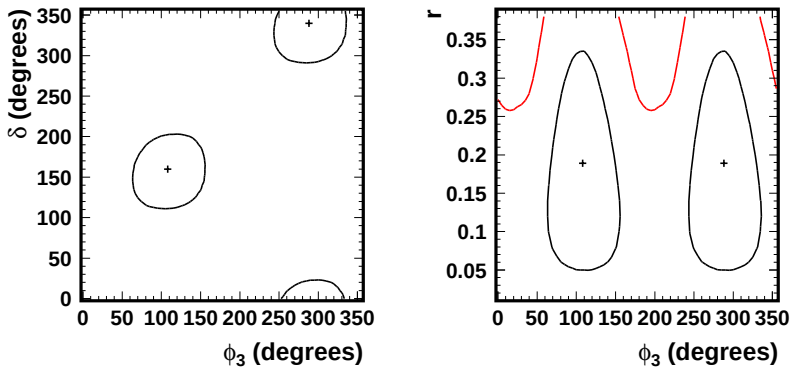
ϕ_3	$81^\circ {}^{+13^\circ}_{-15^\circ}$
r_{D*K}	0.16 ± 0.04
δ_{D*K}	$137^\circ {}^{+13^\circ}_{-16^\circ}$

$B^\pm \to D^* K^\pm$, $D^* \to D\pi^0$



ϕ_3	$64^\circ {}^{+21^\circ}_{-23^\circ}$
r_{D*K}	$0.21^{+0.09}_{-0.08}$
δ_{D*K}	$342^\circ {}^{+21^\circ}_{-23^\circ}$

$B^\pm \to D^* K^\pm$, $D^* \to D\gamma$



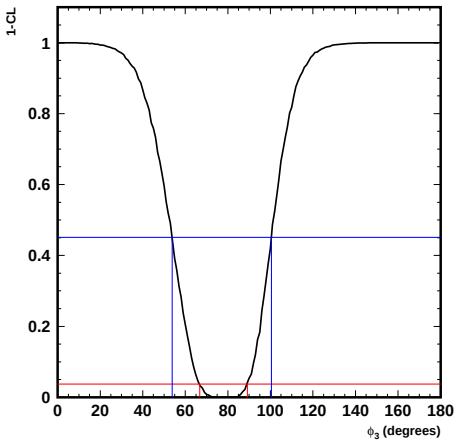
ϕ_3	$108^\circ {}^{+53^\circ}_{-50^\circ}$
r_{D*K}	$0.19^{+0.14}_{-0.12}$
δ_{D*K}	$160^\circ {}^{+48^\circ}_{-55^\circ}$

Systematic errors

- Dominant experimental systematic errors:
  - Background distributions in Dalitz, $(M_{\rm bc}, \Delta E)$ and $(\cos\theta_{\rm thr}, \mathcal{F})$.
  - Efficiency profile
  - Signal distributions in $(M_{\rm bc}, \Delta E)$ and $(\cos\theta_{\rm thr}, \mathcal{F})$.
  - Correlations between Dalitz, $(M_{\rm bc}, \Delta E)$ and $(\cos\theta_{\rm thr}, \mathcal{F})$
  - Background fractions
- Model uncertainty:
  - Non-ideal description of the D decay density $|f_D|^2$.
  - Uncertainty of the phase variations due to model description. $\Delta\phi_3 = 9^\circ$. Can be improved by CLEO-c measurement of $\psi(3770) \to D\overline{D}$.

Combination of all modes NEW

605 fb^{-1} data sample. Belle preliminary



5 variables
1σ CL: 3.74%
2σ CL: 45.1%

ϕ_3	$78.4^\circ {}^{+10.8^\circ}_{-11.6^\circ} \pm 3.6^\circ(\text{syst}) \pm 8.9^\circ(\text{model})$
r_{DK}	$0.160^{+0.040}_{-0.038} \pm 0.011(\text{syst})^{+0.050}_{-0.010}(\text{model})$
δ_{DK}	$136.7^\circ {}^{+13.0^\circ}_{-15.8^\circ} \pm 4.0^\circ(\text{syst}) \pm 22.9^\circ(\text{model})$
r_{D^*K}	$0.196^{+0.072}_{-0.069} \pm 0.012(\text{syst})^{+0.062}_{-0.012}(\text{model})$
δ_{D^*K}	$341.9^\circ {}^{+18.0^\circ}_{-19.6^\circ} \pm 3.0^\circ(\text{syst}) \pm 22.9^\circ(\text{model})$

δ_{D^*K} is defined for $D^0 \to D\pi^0$ state.

$\delta_{D\pi^0 K} - \delta_{D\gamma K}$ is fixed to 180°.

Ambiguity: $(\phi_3, \delta) \to (\phi_3 + \pi, \delta + \pi)$. Solution consistent with the Standard Model is taken $(0 < \phi_3 < \pi)$.

CPV confidence level: $1 - CL = 5.0 \times 10^{-4}$ (3.5σ) including systematic and model uncertainties

Conclusion

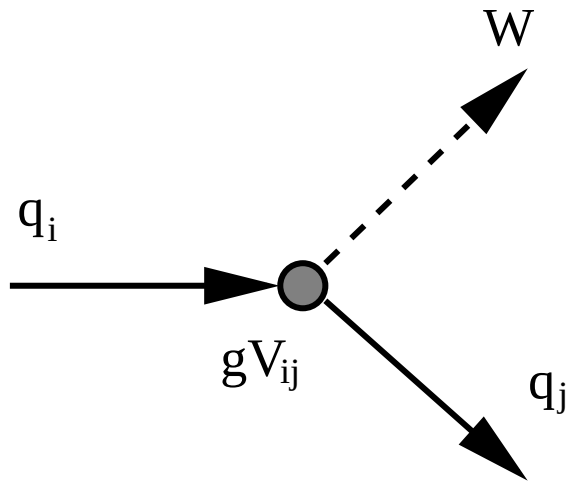
- Belle uses three modes in Dalitz plot analysis to obtain ϕ_3:
  - $B^\pm \to DK^\pm$ and $B^\pm \to D^*K^\pm$ with $D^* \to D\pi^0$: Moriond 2008, arXiv:0803.3375
  - New mode: $B^\pm \to D^*K^\pm$ with $D^* \to D\gamma$.
- Combined results for all modes:
  - $\phi_3 = 78.4^\circ {}^{+10.8^\circ}_{-11.6^\circ} \pm 3.6^\circ(\text{syst}) \pm 8.9^\circ(\text{model})$
  - $r_{DK} = 0.160^{+0.040}_{-0.038} \pm 0.011(\text{syst})^{+0.050}_{-0.010}(\text{model})$
  - $r_{D^*K} = 0.196^{+0.072}_{-0.069} \pm 0.012(\text{syst})^{+0.062}_{-0.012}(\text{model})$
- CP violation significance: 3.5σ (including systematic and model uncertainty).
- Error of ϕ_3 starts to be saturated by model uncertainty. Error due to $\overline{D}^0 \to K^0_S\pi^+\pi^-$ amplitude description can be as low as $2^\circ - 3^\circ$ using CLEO-c quantum correlated $\psi(3770) \to D\overline{D}$ analysis [arXiv:0903.1681]

Weak decays and CKM matrix

Coupling constant g.

Cabibbo-Kobayashi-Maskawa mixing matrix V_{ij}.

Unitarity: $V_{ij}^* V_{jk} = \delta_{ik}$.



V_{ij} parametrization (Wolfenstein):

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

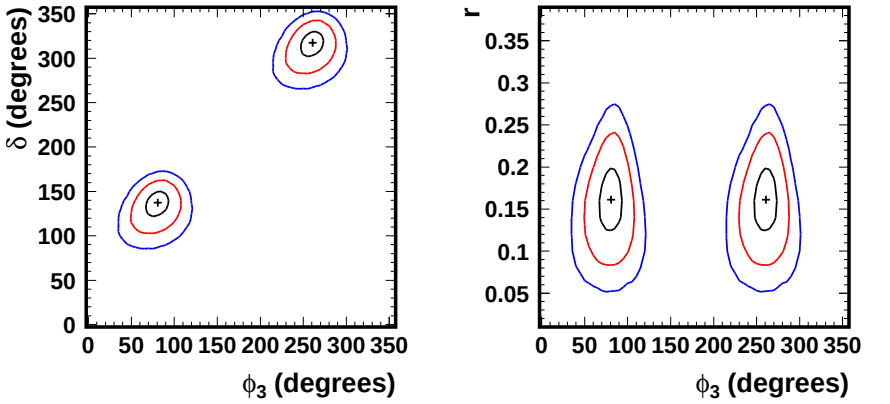
$\lambda = 0.2235 \pm 0.0033, \quad A = 0.81 \pm 0.08$

$|\rho - i\eta| = 0.36 \pm 0.09, \quad |1-\rho-i\eta| = 0.79 \pm 0.19$.

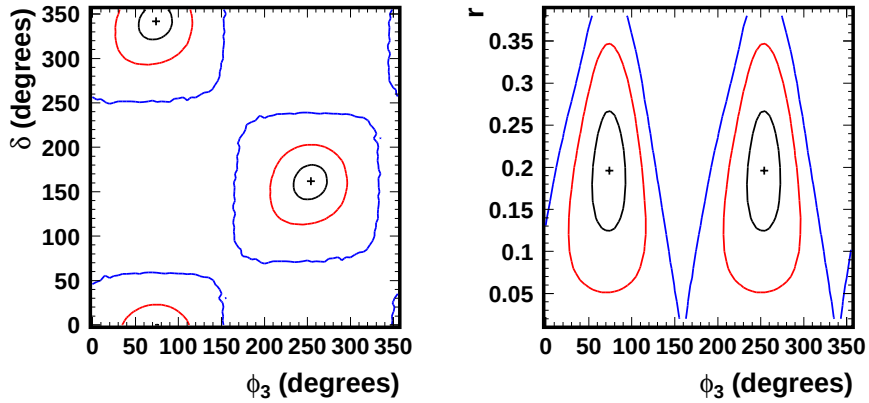
Fit results in (ϕ_3, r, δ)

Feldman-Cousins stat. treatment to translate $(x_\pm, y_\pm) \to (r, \phi_3, \delta)$

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



$B^\pm \to D^* K^\pm$ ($D\pi^0$ and $D\gamma$)



	$B^+ \to DK^+$ mode	$B^+ \to D^* K^+$ mode
ϕ_3	$80.8^\circ {}^{+13.1^\circ}_{-14.3^\circ} \pm 5.0^\circ \pm 8.9^\circ$	$73.9^\circ {}^{+18.9^\circ}_{-20.2^\circ} \pm 4.2^\circ \pm 8.9^\circ$
r	$0.161^{+0.040}_{-0.038} \pm 0.011^{+0.050}_{-0.010}$	$0.196^{+0.073}_{-0.072} \pm 0.013^{+0.062}_{-0.012}$
δ	$137.4^\circ {}^{+13.0^\circ}_{-15.7^\circ} \pm 4.0^\circ \pm 22.9^\circ$	$341.7^\circ {}^{+18.6^\circ}_{-20.9^\circ} \pm 3.2^\circ \pm 22.9^\circ$

δ_{D^*K} is defined for $D^0 \to D\pi^0$ state. $\delta_{D\pi^0 K} - \delta_{D\gamma K}$ is fixed to 180°.