CP violation in B decays with Belle and BABAR

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BELLE

BABAR

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Contents of talk today

- Final sin2ϕ_1 from 1st generation B-factories
- ϕ_3 measurements with new analysis techniques
- Prospects in near future

Quark mixing and CP violation

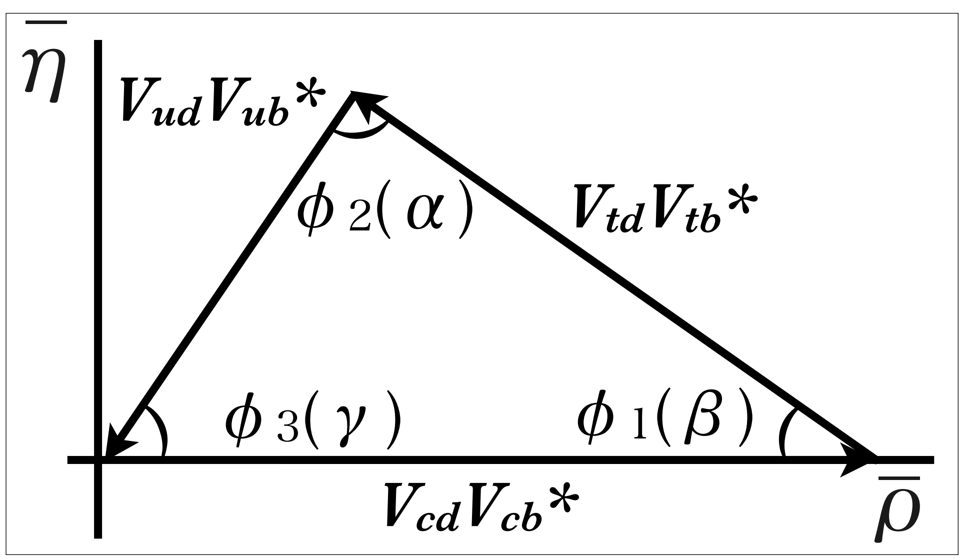
3-generation quark mixing : Cabbibo-Kobayashi-Maskawa matrix

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

Wolfenstein representation

CP violation is induced by complex phase of CKM matrix

$$\Sigma_i V_{ij}{}^* V_{ik} = \delta_{jk} \Rightarrow V_{ud} V_{ub}{}^* + V_{cd} V_{cb}{}^* + V_{td} V_{tb}{}^* = 0 \ (k = b)$$



Unitary triangle

CP violation parameters

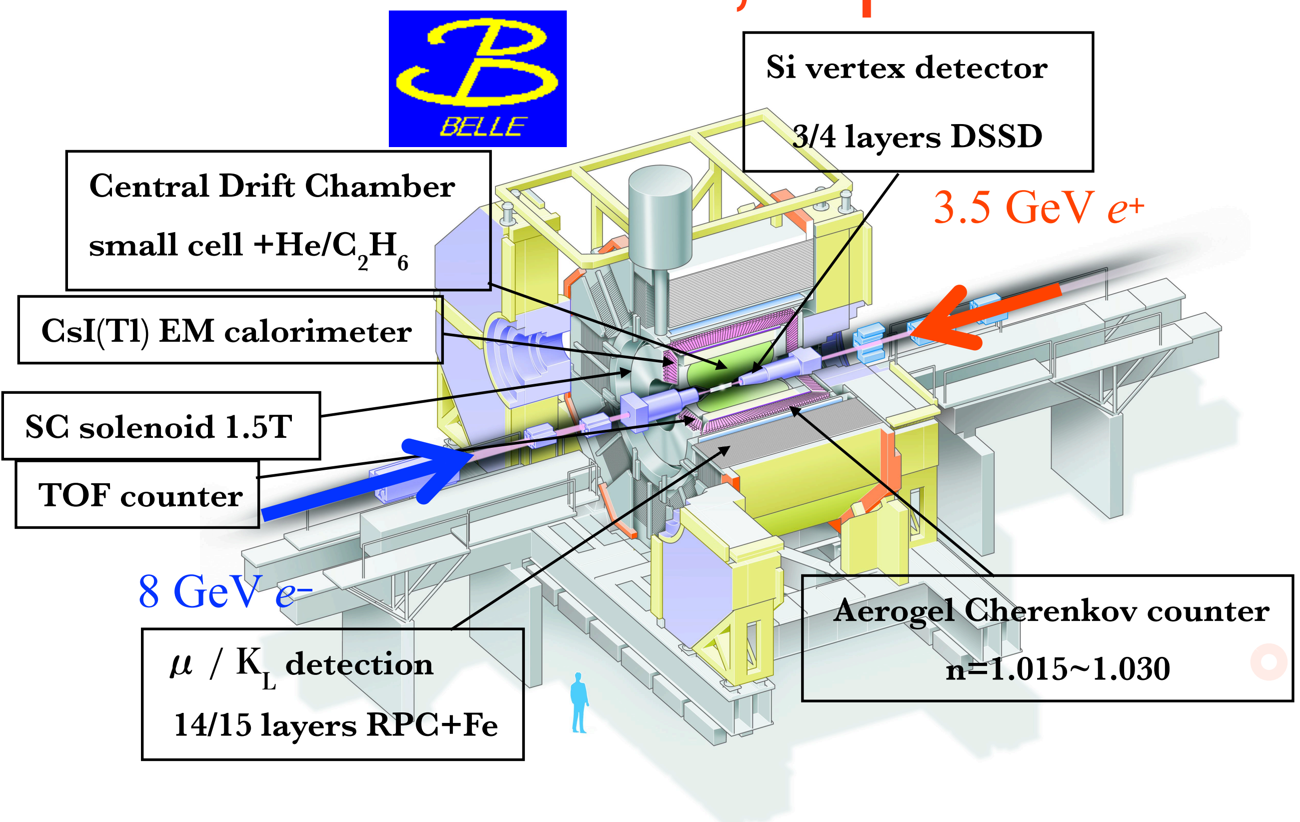
$\phi_1(=\beta) = \arg(V_{cd} V_{cb}{}^* / V_{td} V_{tb}{}^*)$

$\phi_2(=\alpha) = \arg(V_{ud} V_{ub}{}^* / V_{td} V_{tb}{}^*)$

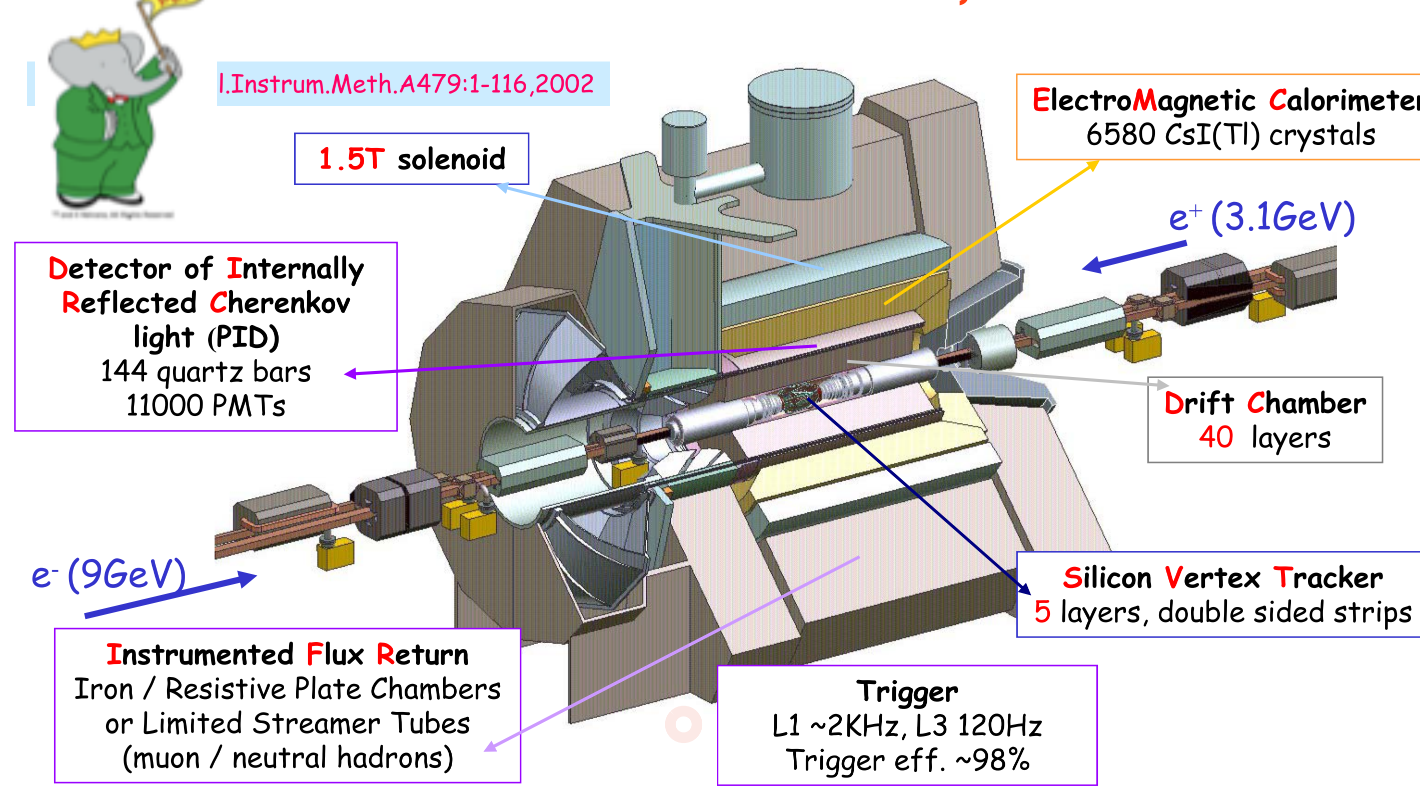
$\phi_3(=\gamma) = \arg(V_{cd} V_{cb}{}^* / V_{ud} V_{ub}{}^*)$

B-factories

KEKB at KEK,Japan

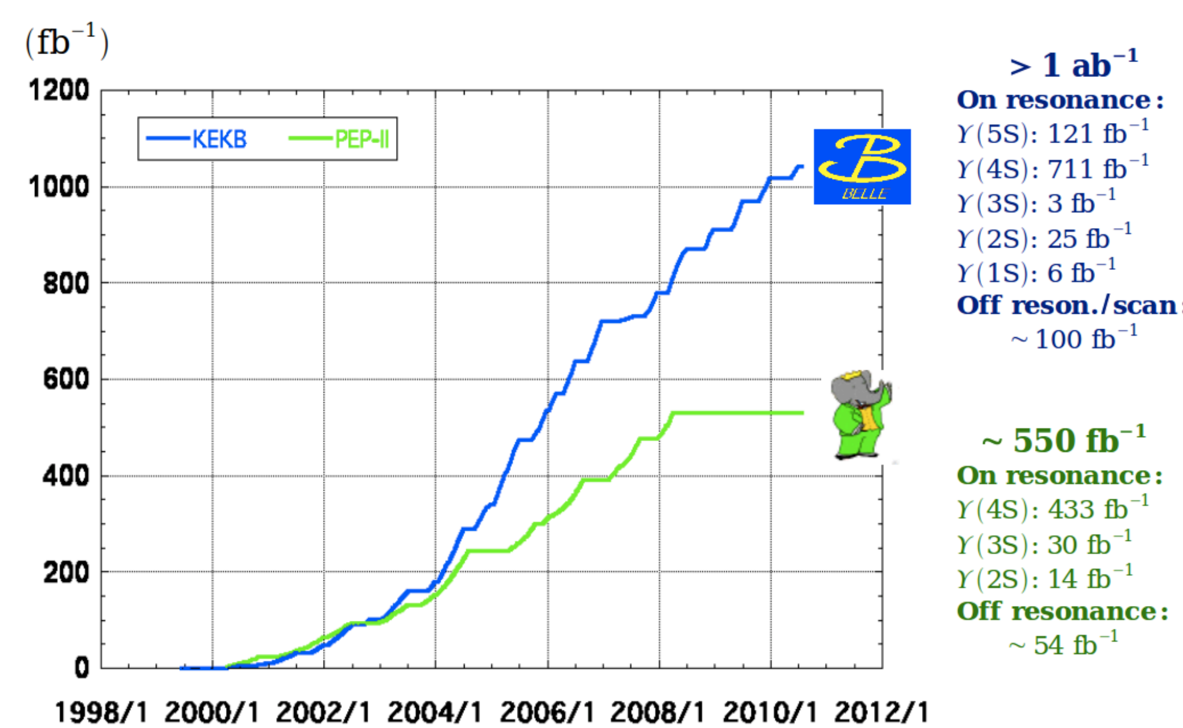


PEP-II at SLAC,USA



772M + 463M $B\bar{B}$ accumulated!

Integrated luminosity of B factories



Measurement of sin2ϕ_1

Time-dependent CP violation:

Quantum interference between B^0–$\bar{B}^0$ mixing and B^0 decay to CP eigenstate.

$$A_{CP}(\Delta t) = \frac{\mathcal{P}(\overline{B^0}(\Delta t) \to f_{CP}) - \mathcal{P}(B^0(\Delta t) \to f_{CP})}{\mathcal{P}(\overline{B^0}(\Delta t) \to f_{CP}) + \mathcal{P}(B^0(\Delta t) \to f_{CP})}$$

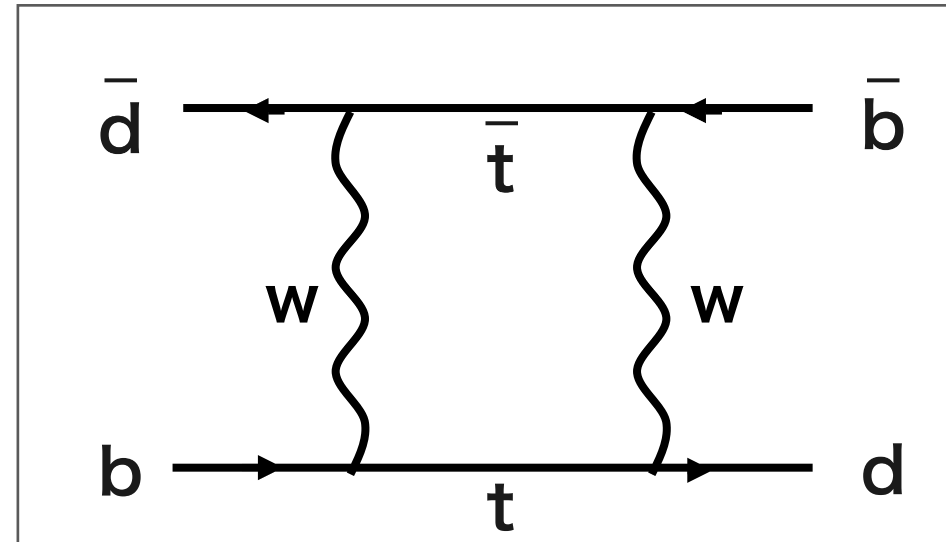
$$= S \sin \Delta m \Delta t + A \cos \Delta m \Delta t$$

S: Mixing induced CPV parameter

A(=−C): Direct CPV parameter

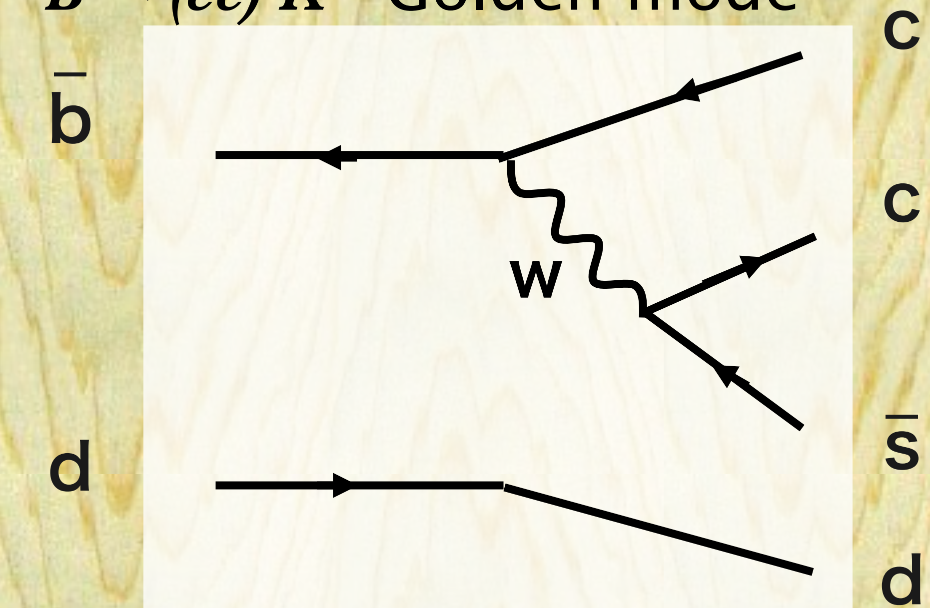
Δm: B-B mass difference

Δt: B-B decay time difference



— $b \to c\bar{c}s$ tree diagram

$B^0 \to (c\bar{c})\, K^0$ "Golden mode"



$(c\bar{c}) = J/\psi, \psi(2S), \chi_{c1}, \eta_c$...

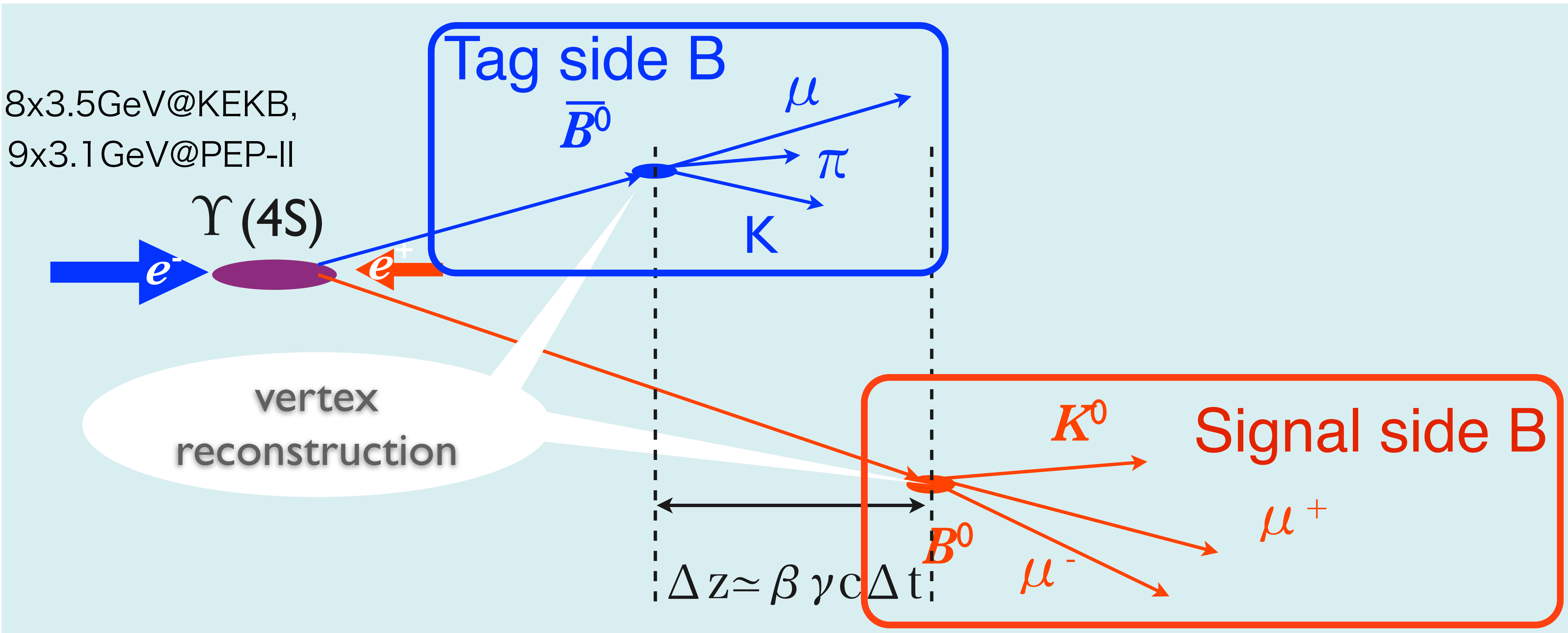
$S = -\xi_f \sin 2\phi_1$

ξ_f: CP eigenvalue :

-1 for $(c\bar{c})K^0_S$, $+1$ for $(c\bar{c})K^0_L$

Principle of sin2ϕ_1 measurement

When (Δt) / Which B^0 (flavor) decay into CP eigenstate?



- Reconstruct B^0 (beam constraint mass, energy, momentum etc.)
- Tag B^0 flavor (charge of decay products of accompany B^0)

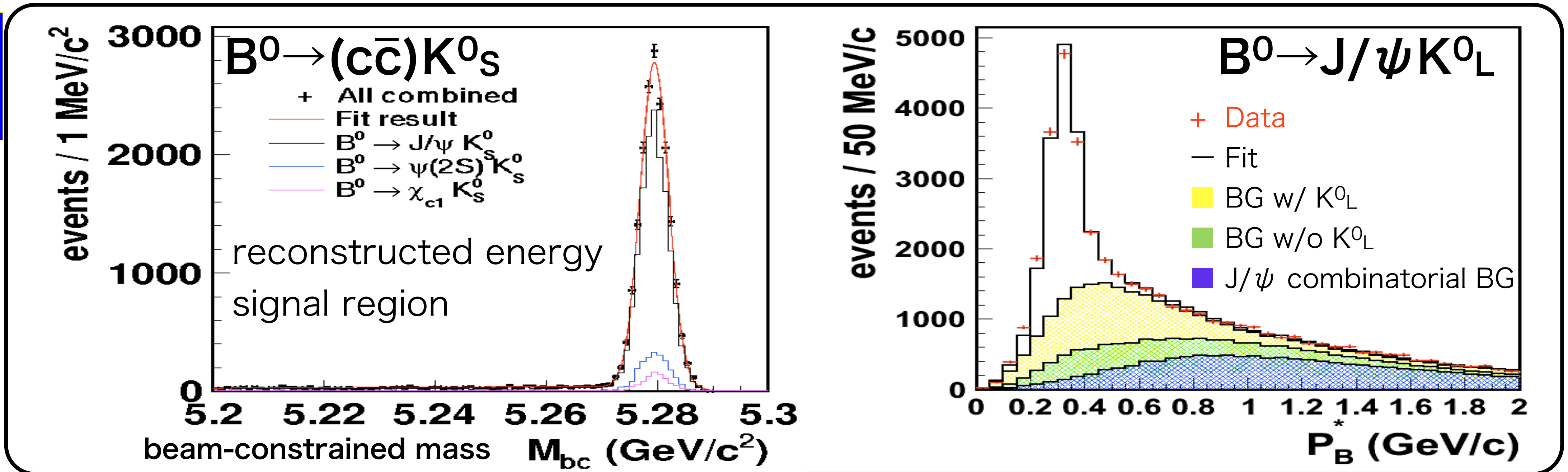
$\overline{B}^0 \rightarrow D^{*+} l^- \nu$, $\overline{B}^0 \rightarrow D^{*\pm} \rightarrow D^0 \pi^+$

$\hookrightarrow K^- l^+ \nu$

- Δt measurement from decay vertices

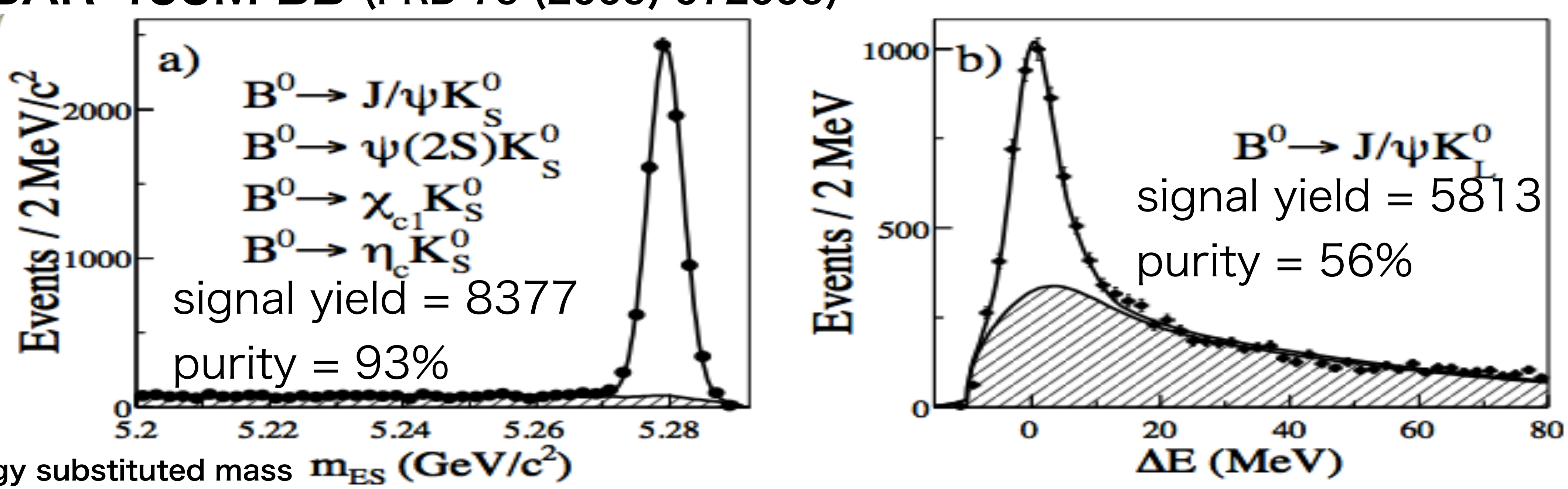
Reconstruction of CP sample

Belle 772M $B\bar{B}$ (Preliminary)



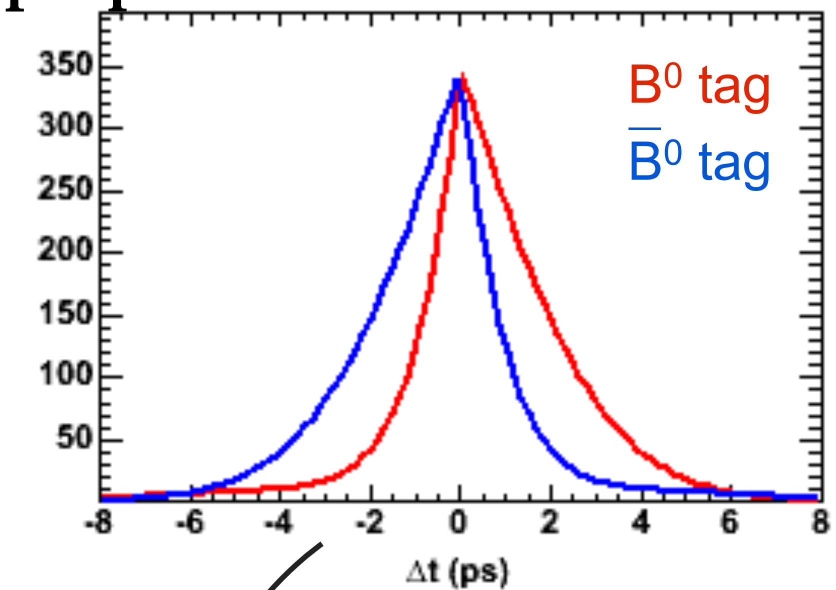
	$J/\psi K^0_S$	$J/\psi K^0_L$	$\psi(2S)K^0_S$	$\chi_{c1}K^0_S$
Signal yield	12681±114	10041±154	1981±46	949±33
Purity (%)	97	63	93	89

BABAR 465M $B\bar{B}$ (PRD 79 (2009) 072009)



Time-dependent CPV measurement

proper-time Δt distribution



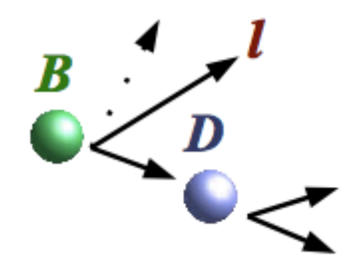
Time dependent decay rate

$$\mathcal{P}_{sig} = \frac{1}{4\tau} e^{-\frac{|\Delta t|}{\tau}} q(\mathrm{A}\cos\Delta m\Delta t + \mathrm{S}\sin\Delta m\Delta t)$$

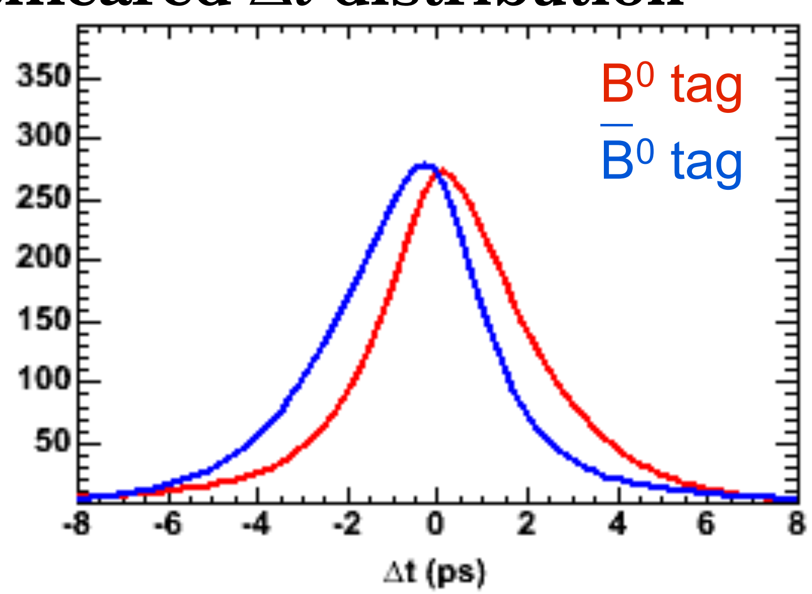
τ : B lifetime

Δm : B-$\overline{\mathrm{B}}$ mass difference

- Detector resolution
- Non-primary tracks from companion B
- Kinematic approximation: $\Delta z \simeq \beta\gamma c \Delta t$
- Failure of B^0 flavor tagging



smeared Δt distribution



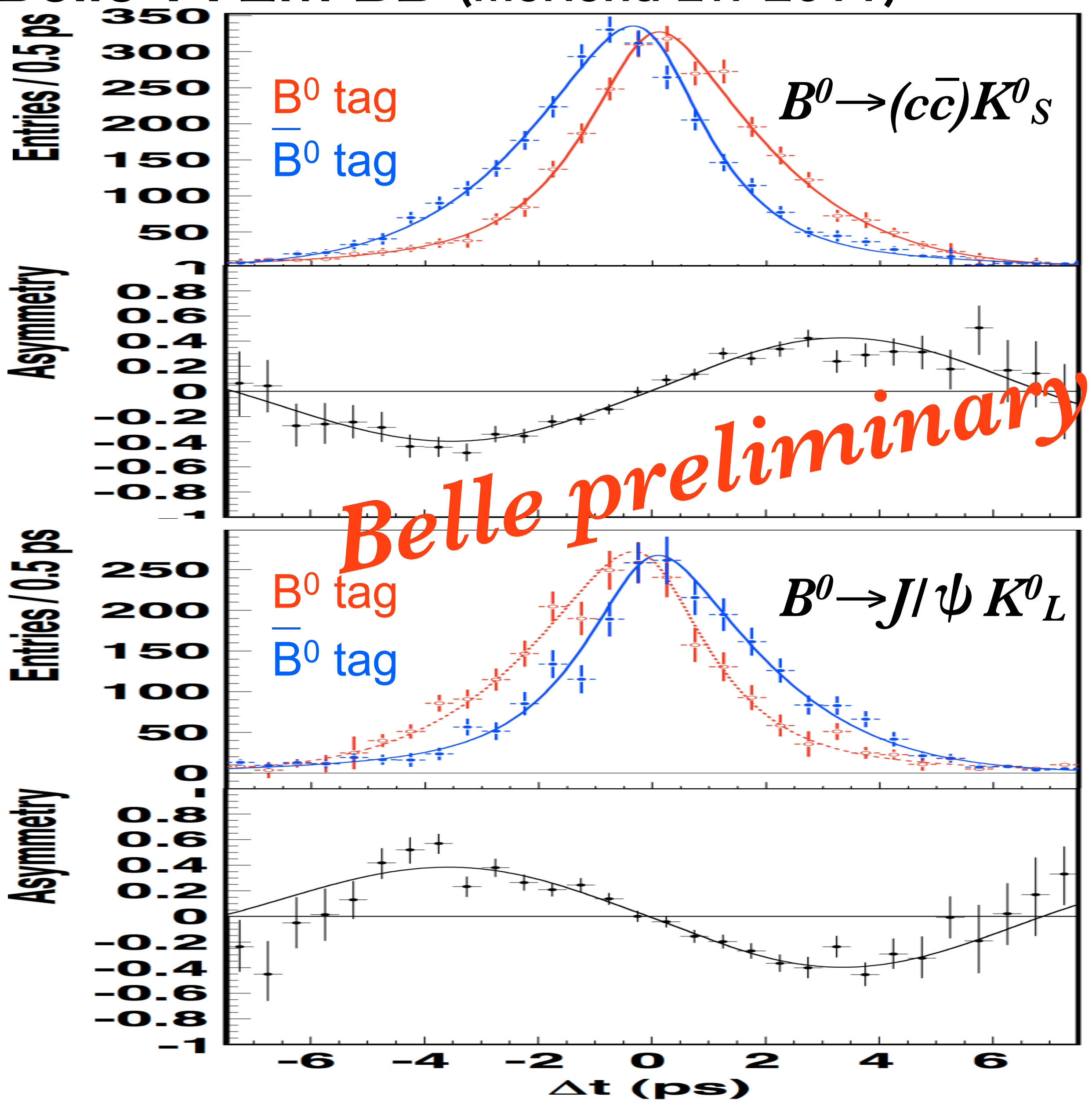
$$\mathcal{P}_{sig} = \frac{1}{4\tau} e^{-\frac{|\Delta t|}{\tau}} (1-2w)\, q(\mathrm{A}\cos\Delta m\Delta t + \mathrm{S}\sin\Delta m\Delta t) \otimes R(\Delta t)$$

flavor tagging quality   resolution function

→ Determined using flavor specific null-CPV control sample ($B^0 \to D^{(*)}h$, $B^0 \to D^* l \nu$)

Measurement of sin2ϕ_1

Belle 772M $B\bar{B}$ (Moriond EW 2011)



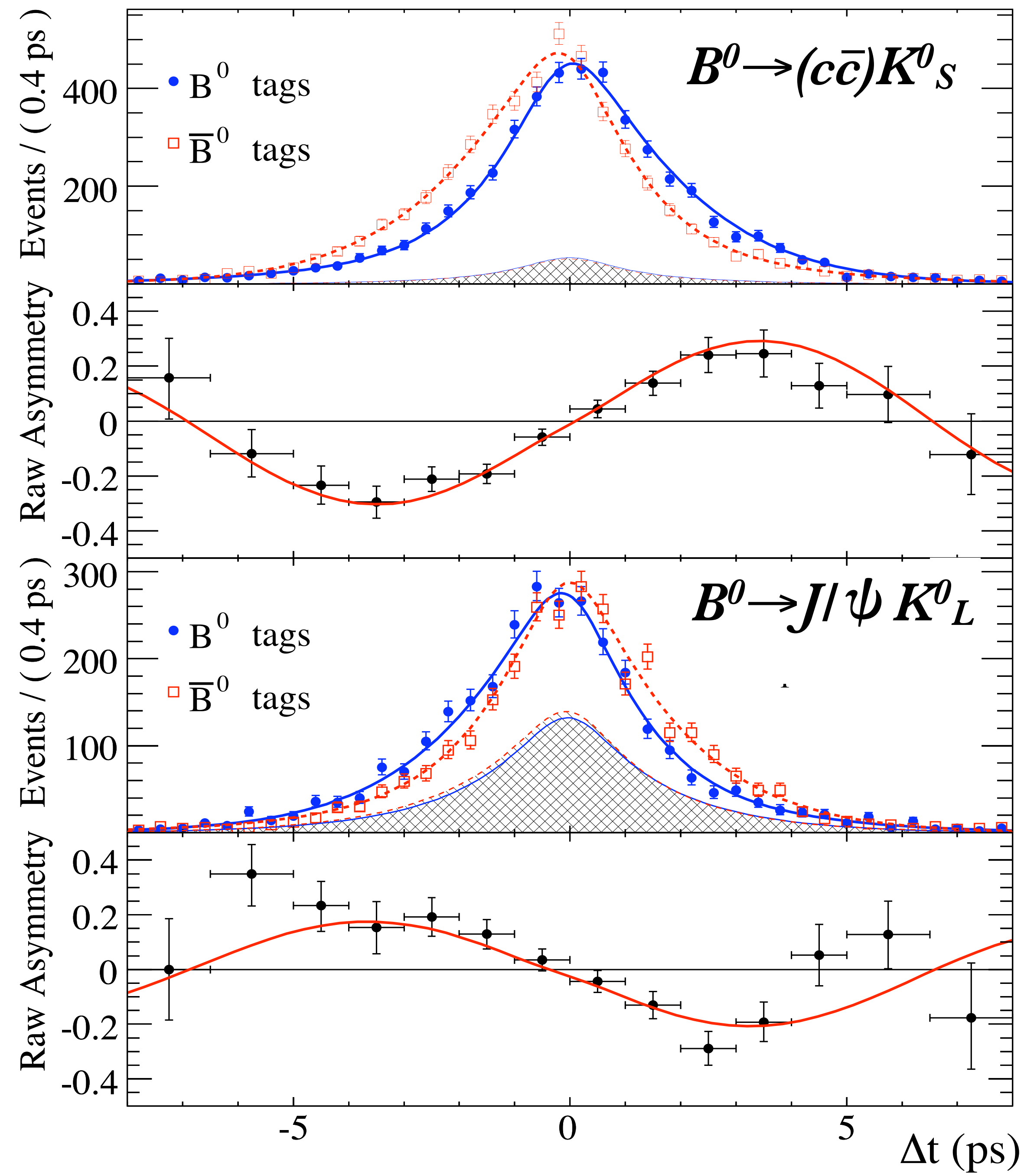
background subtracted,
good flavor tag quality only

$B^0 \to (c\bar{c})K^0_S$ $B^0 \to J/\psi K^0_L$ combined

sin2ϕ_1= 0.668±0.023±0.013

A = 0.007±0.016±0.013

BABAR 465M $B\bar{B}$ (PRD 79 (2009) 072009)

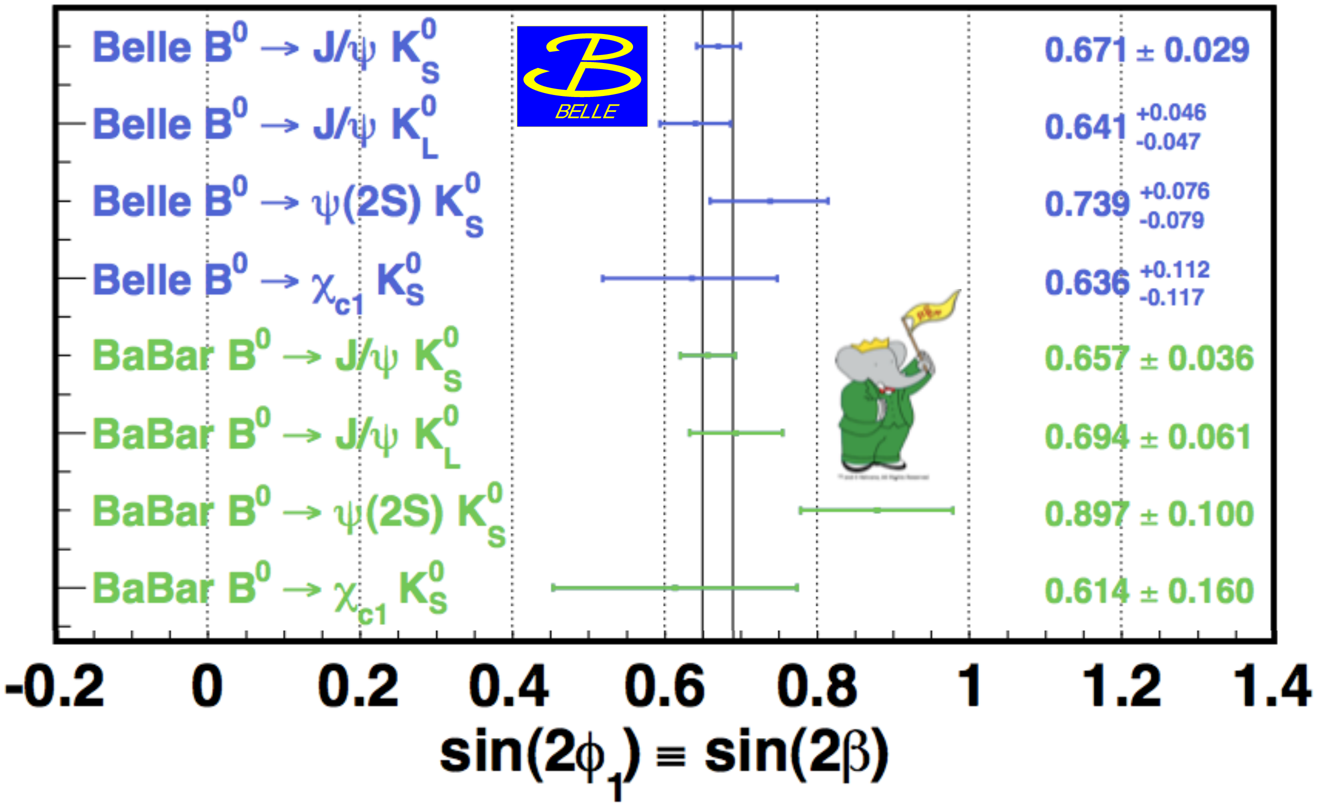


$B^0 \to (c\bar{c})K^0_S$ $B^0 \to J/\psi K^0_L$ combined

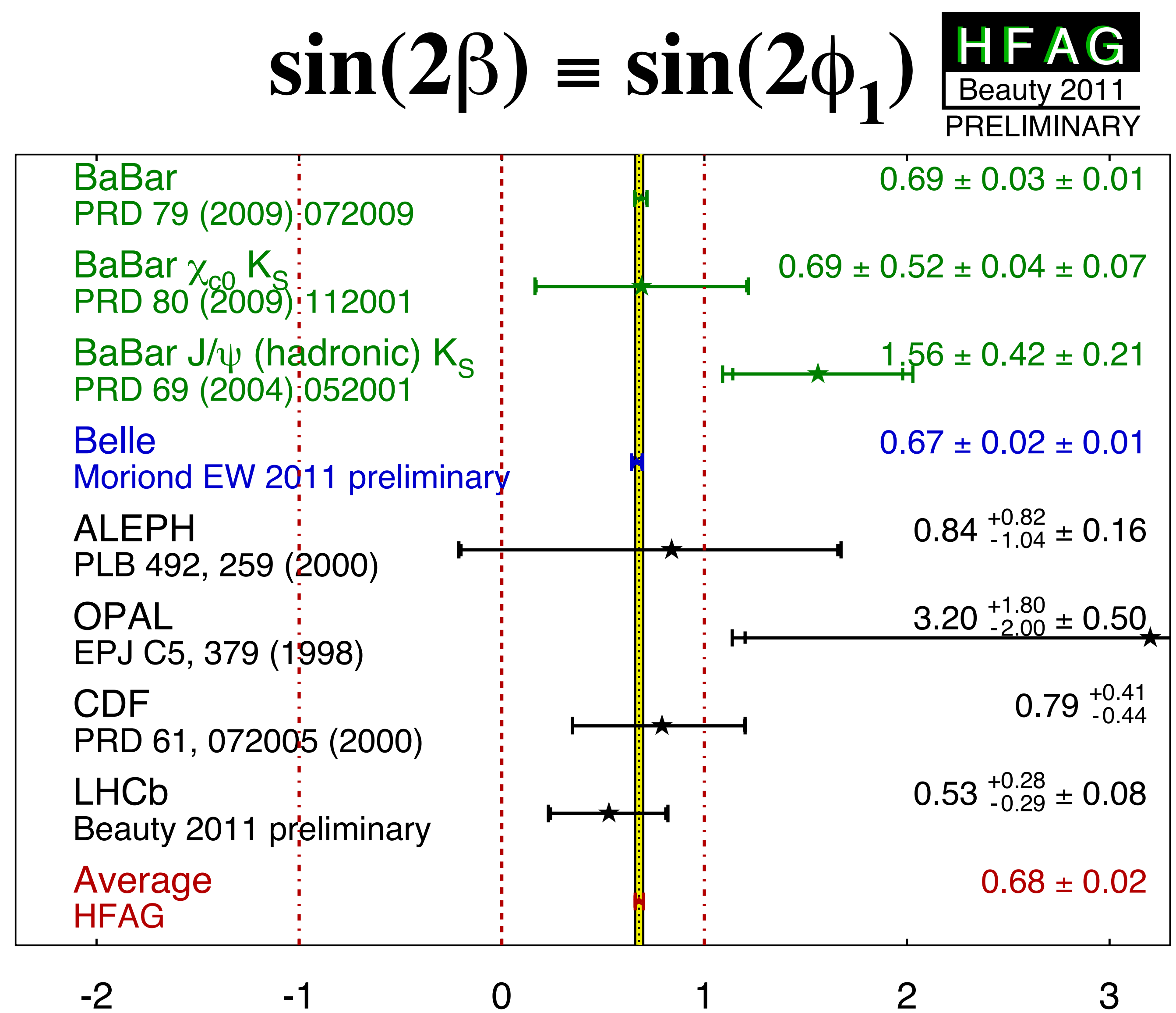
sin2ϕ_1= 0.687±0.028±0.012

A = -0.024±0.020±0.016

Measurement of sin2ϕ_1



Both Belle and BABAR observes CP violation in all decay modes



sin2ϕ_1 is mainly determined by results of B-factories

ϕ_3 determination

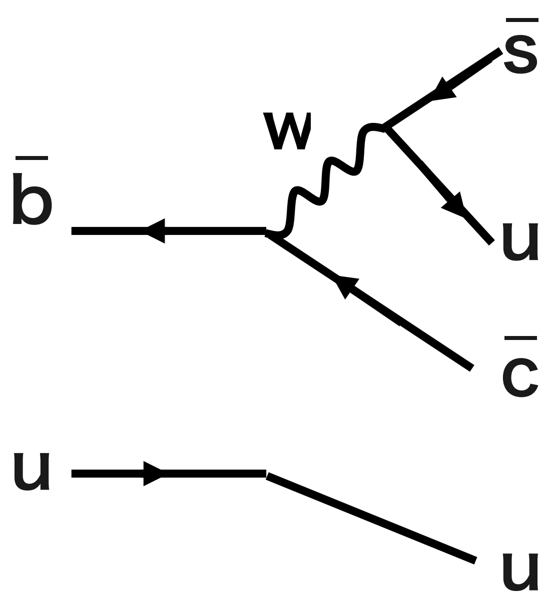
Measurements using interference between V_{ub} contribution and another weak vertex.

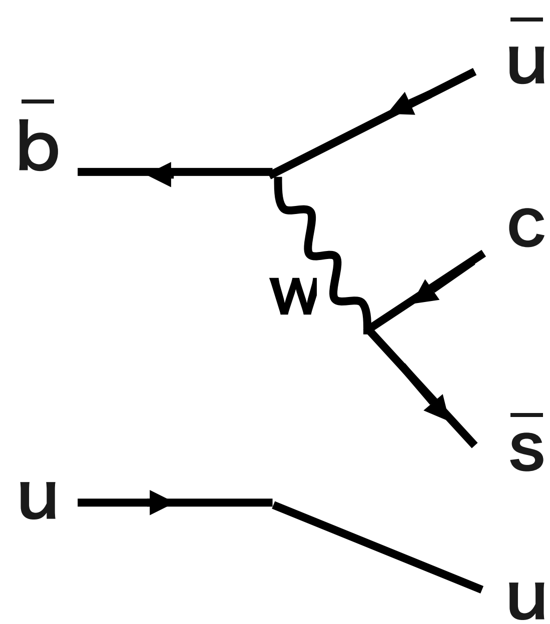
Relative phase of $B^{\pm} \rightarrow DK^{\pm}$

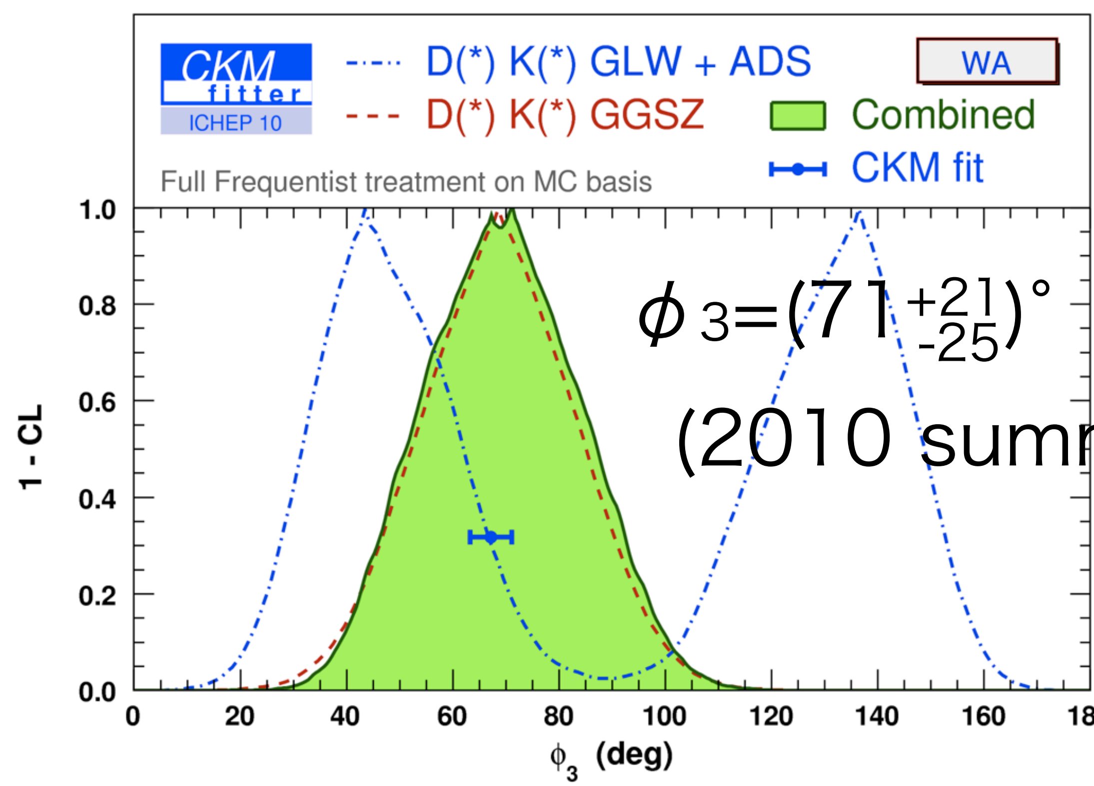
$$|\tilde{D}\rangle = |D^0\rangle + re^{i\theta}|\bar{D}^0\rangle$$

$$\theta = \pm\phi_3 + \delta$$

(weak phase) + (strong phase)







$\phi_3 = (71^{+21}_{-25})^{\circ}$

(2010 summer)

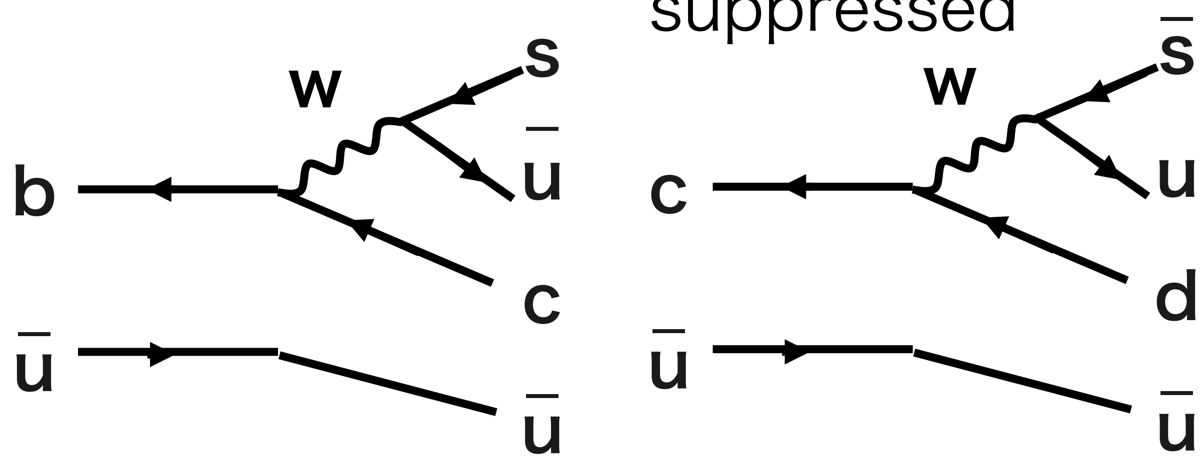
Several decays modes of D meson are used to determine ϕ_3

Measurement of ϕ_3 with ADS

D. Atwood, I. Dunietz and A. Soni,
PRL78, 3357 (1997); PRD 63, 036005 (2001)

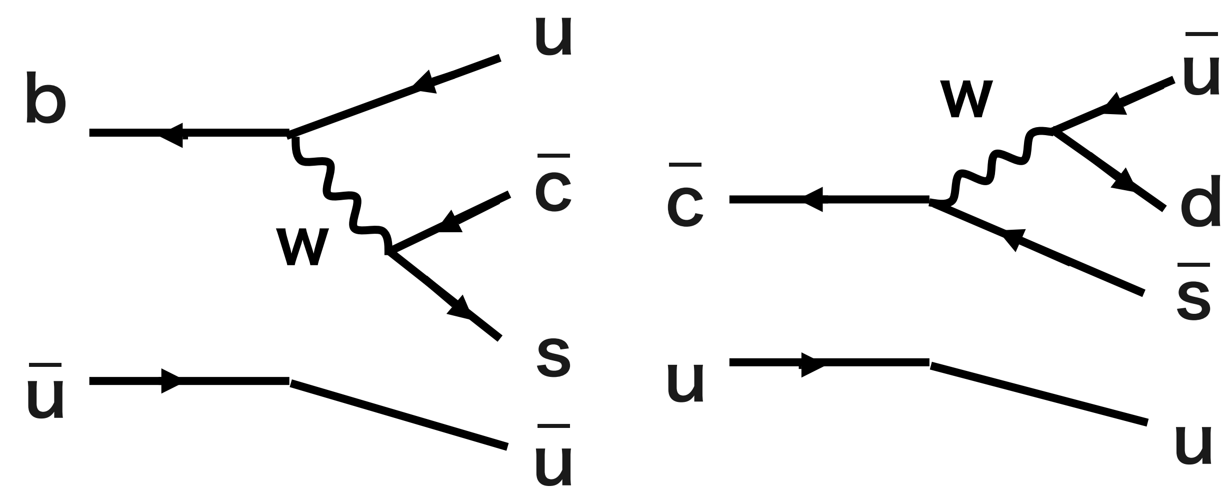
$B^- \to D^0 K^-$ color-allowed

$D^0 \to K^+ \pi^-$ doubly Cabibbo-suppressed



$B^- \to \bar{D}^0 K^-$ color-suppressed

$\bar{D}^0 \to K^+ \pi^-$ Cabibbo-allowed



⇒ Magnitudes of interfering amplitudes are comparable

→CP violation effects are enhanced

$$\mathcal{R}_{DK} \equiv \frac{\mathcal{B}([K^+\pi^-]_D K^-) + \mathcal{B}([K^-\pi^+]_D K^+)}{\mathcal{B}([K^-\pi^+]_D K^-) + \mathcal{B}([K^+\pi^-]_D K^+)}$$

$$= r_B^2 + r_D^2 + 2 r_B r_D \cos\delta \cos\phi_3$$

$$r_B \equiv \left| \frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right| , \quad \delta \equiv \delta_B + \delta_D ,$$

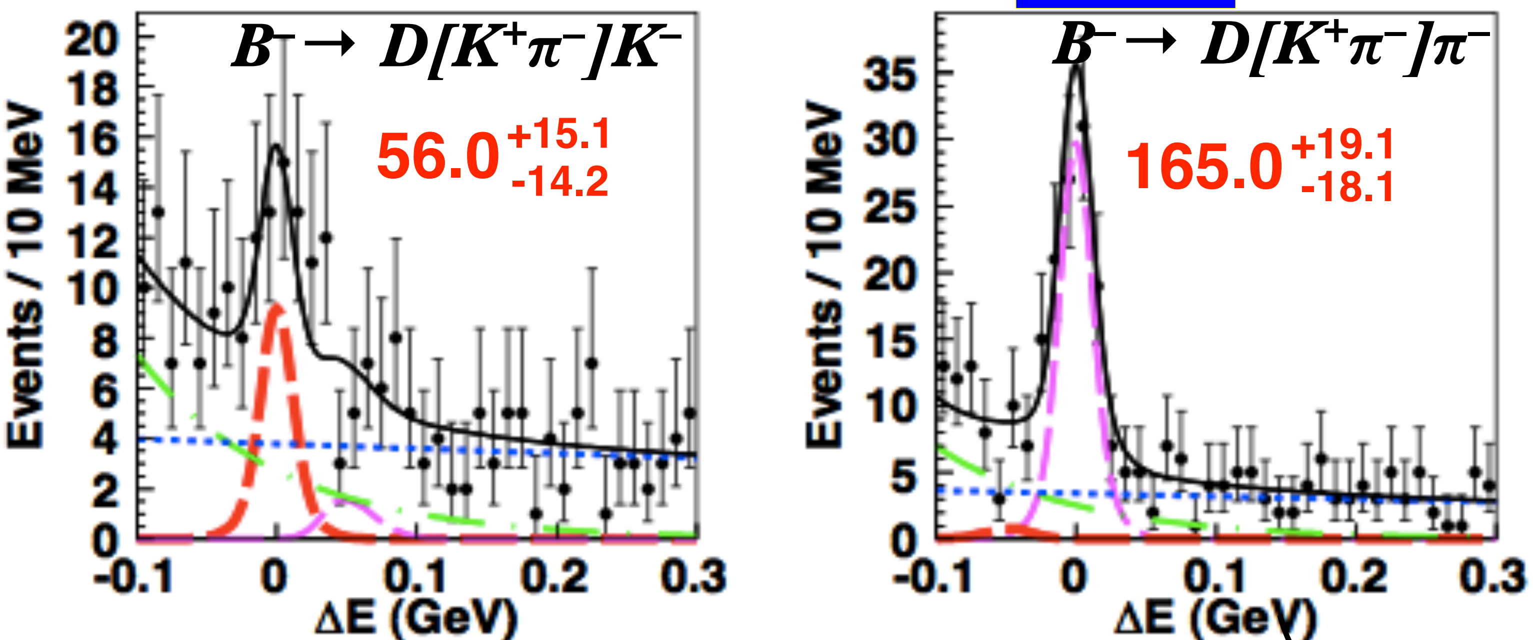
$$r_D \equiv \left| \frac{A(D^0 \to K^+\pi^-)}{A(D^0 \to K^-\pi^+)} \right|$$

$$\mathcal{A}_{DK} \equiv \frac{\mathcal{B}([K^+\pi^-]_D K^-) - \mathcal{B}([K^-\pi^+]_D K^+)}{\mathcal{B}([K^+\pi^-]_D K^-) + \mathcal{B}([K^-\pi^+]_D K^+)}$$

$$= 2 r_B r_D \sin\delta \sin\phi_3 / R_{DK}$$

Results of ADS method

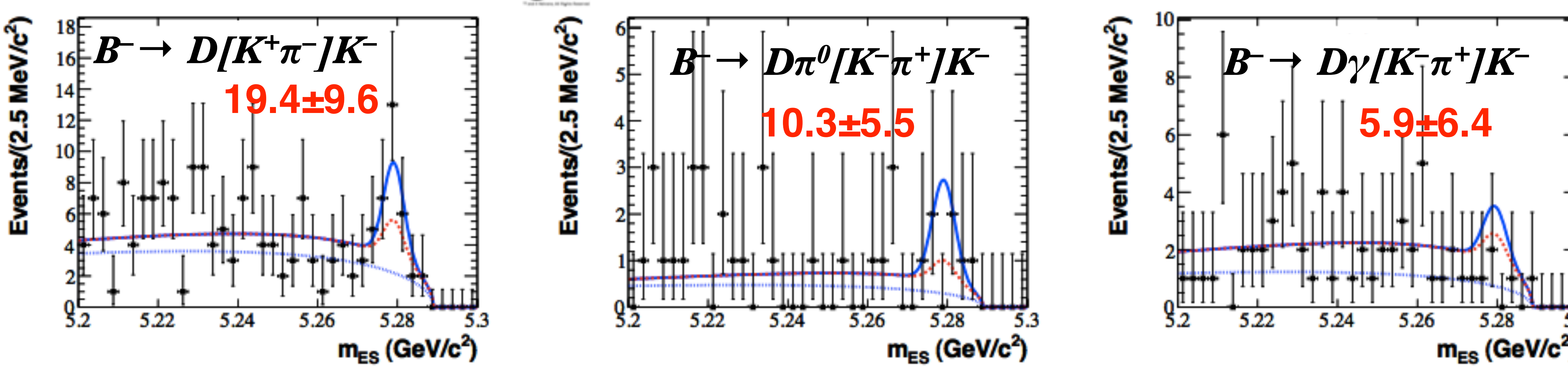
Belle 772M $B\bar{B}$
(arXiv:1103.5951(hep-ex))



First evidence of suppressed $B \to D[K^+\pi^-]K$ decay signal
due to increasing of data and cleverer continuum background suppression based on neural-net

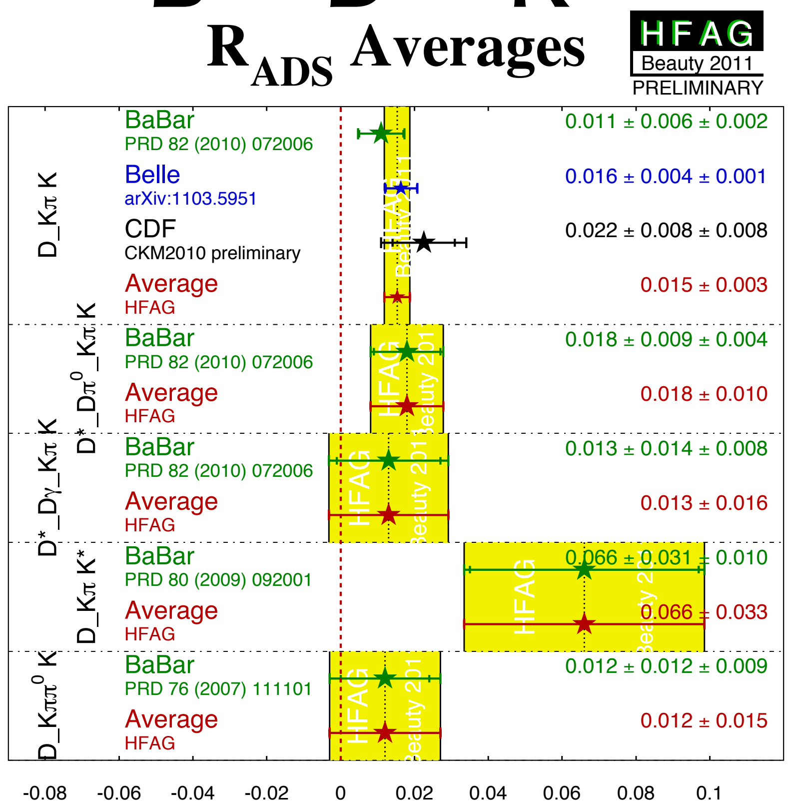
→ Larger signal yield but sensitivity of ϕ_3 is lower due to smallness of r_B

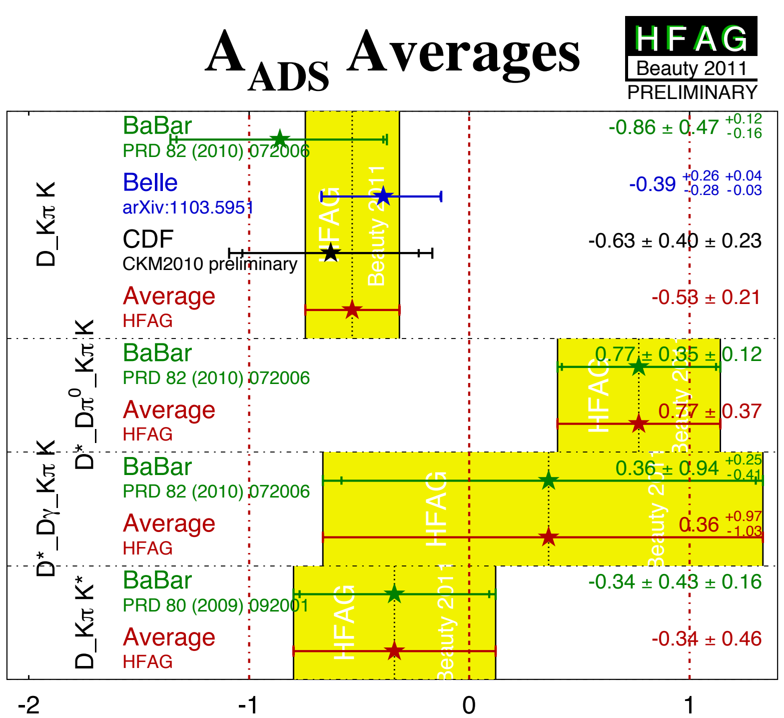
BABAR 467M $B\bar{B}$
(PRD82 072006 (2010))



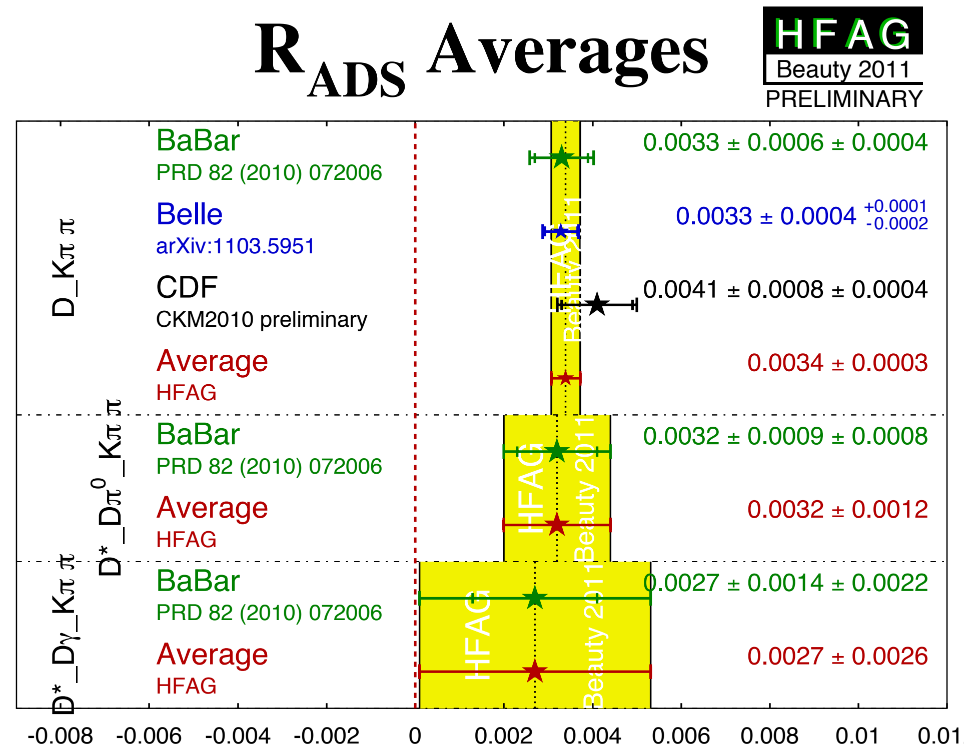
Results of ADS method

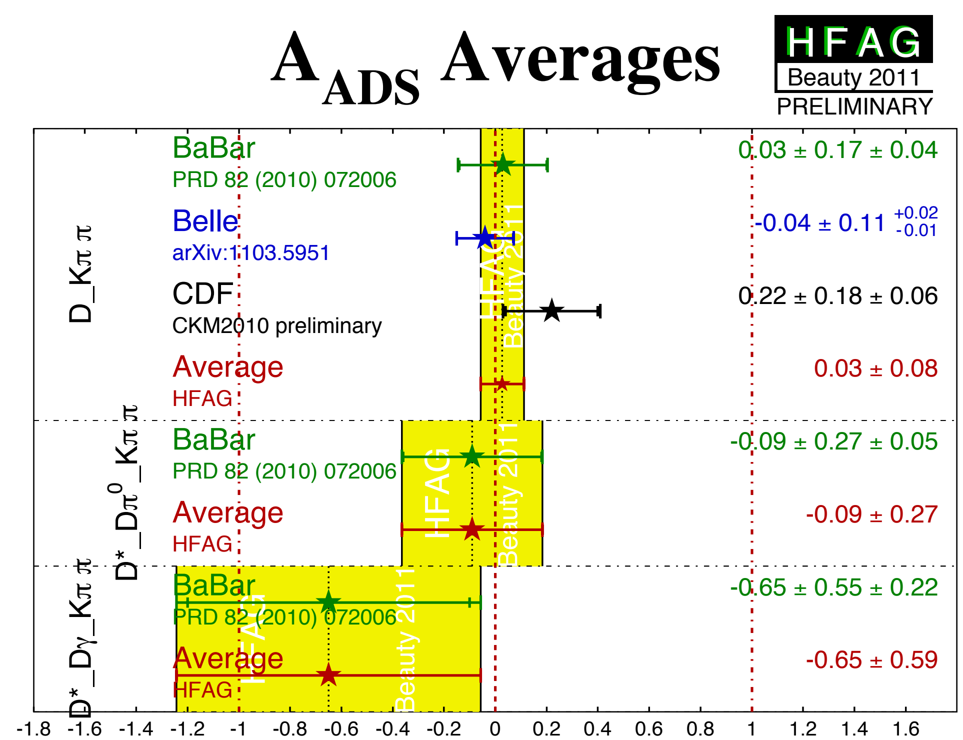
$B^- \to D^{(*)0} K^{(*)-}$





$B^- \to D^{(*)0} \pi^-$





- Most precise measurement by Belle in $D \to K\pi$
- BABAR attempted to use D*K and DK* as well

Measurement of ϕ_3 with GGSZ

Dalitz plot analysis using $D \to K_S^0 \pi^+ \pi^-$ 3-body decay

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

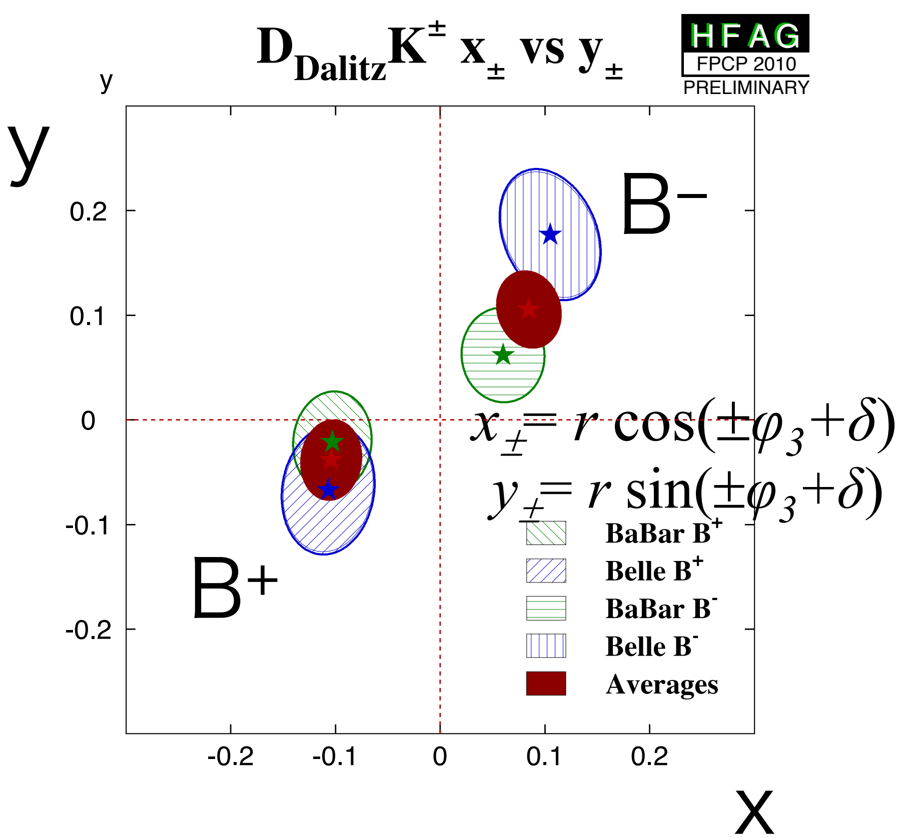
Dalitz plot density: $d\sigma_\pm(m_+^2, m_-^2) \sim |M_\pm|^2 dm_+^2 dm_-^2$

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

$$m_+^2 = m_{K_S\pi^+}^2, \quad m_-^2 = m_{K_S\pi^-}^2$$

$D^0 \to K_S^0 \pi^+ \pi^-$ amplitude f_D : fit to flavor-tagged $D^* \to D^0 \pi$ sample

(Phase term is based on model assumption)



$\phi_3 = (78\,^{+11}_{-12} \pm 4 \pm 9)^\circ$

(Belle, DK^- and D^*K^- combined)

$(68\,^{+15}_{-14} \pm 4 \pm 3)^\circ$

(BABAR, DK^-, D^*K^- and DK^{*-} combined)

3rd errors are from Dalitz model

→ becomes dominant in future

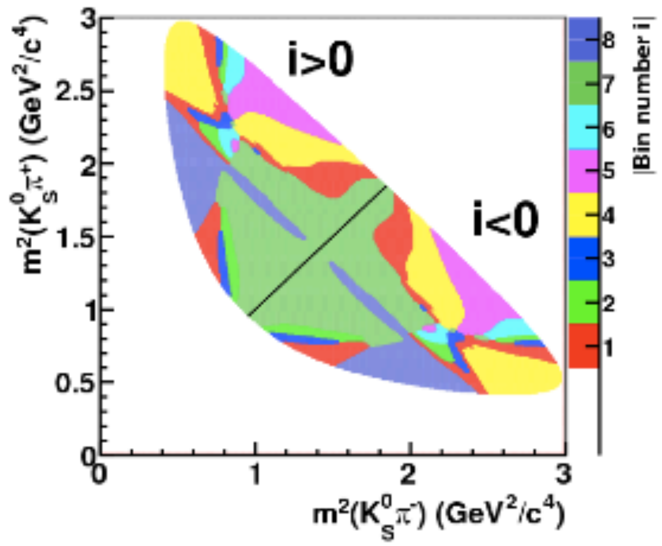
high-statistic experiments

Measurement of ϕ_3 with GGSZ

Binned Dalitz plot analysis : Model independent

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

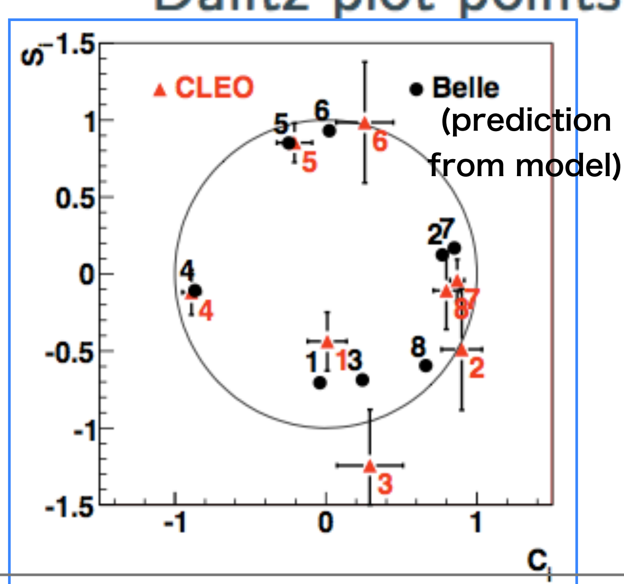
A. Bondar, A. Poluektov, EPJ C 47, 347 (2006); EPJ C 55, 51 (2008)



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

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

- $M_i^{\pm}$: 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 $(m^2_{K_S^0\pi^-}, m^2_{K_S^0\pi^+})$:



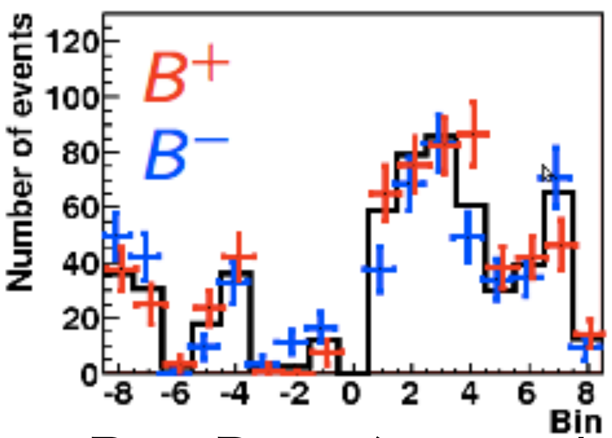
$$c_i = \langle \cos\Delta\delta_D \rangle, \quad s_i = \langle \sin\Delta\delta_D \rangle$$

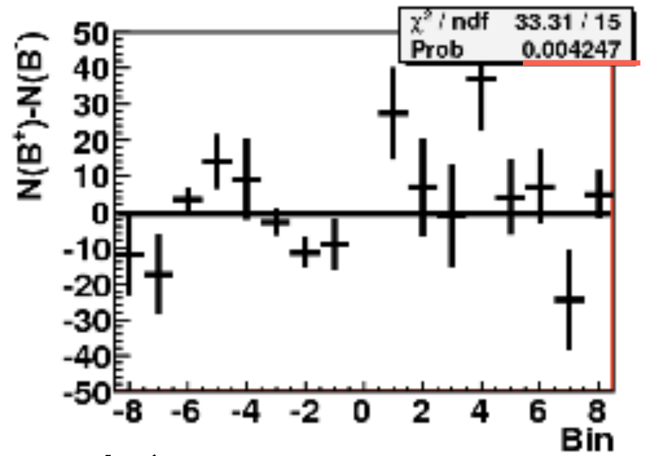
→ estimated from quantum correlations between D^0 and $\bar{D}^0$ in $\psi(3770) \to D^0\bar{D}^0$ decays
CLEO collaboration, PRD 82, 112006 (2010)

⇒ No model uncertainty

Measurement of ϕ_3 with GGSZ

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





→significant direct CP-violation

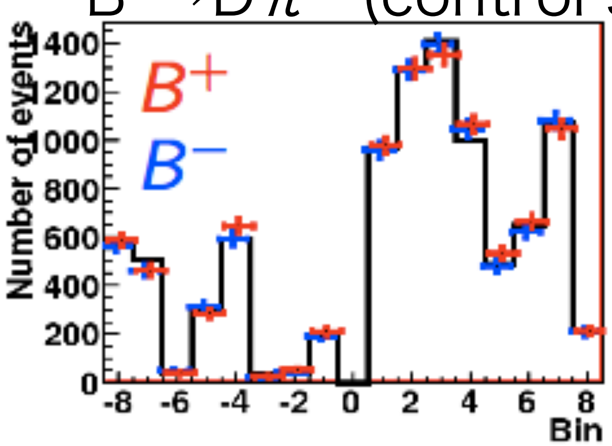
$$\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.2 \pm 4.3)^{\circ}$$

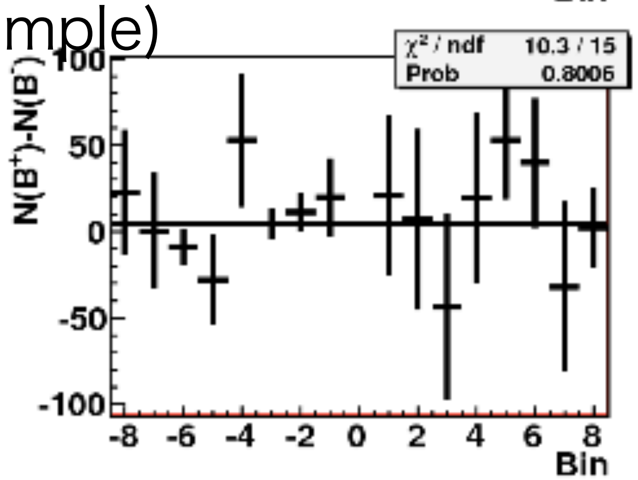
$$r_B = 0.145 \pm 0.030 \pm 0.011 \pm 0.011$$

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

Belle preliminary

$B^{\pm} \to D\pi^{\pm}$ (control sample)





3rd errors are came from uncertainty of c_i and s_i

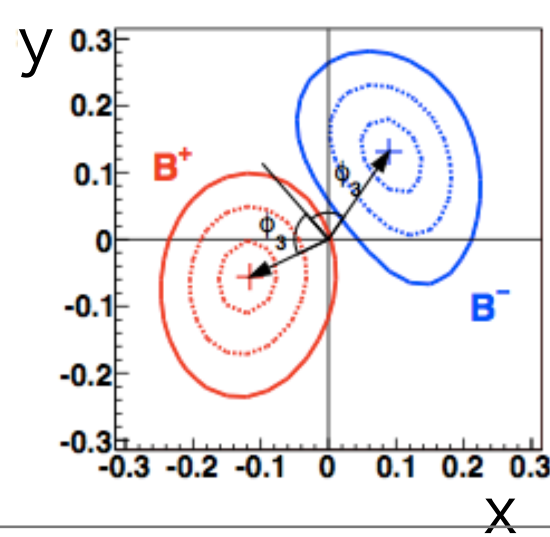
→ improved by charm-factory results

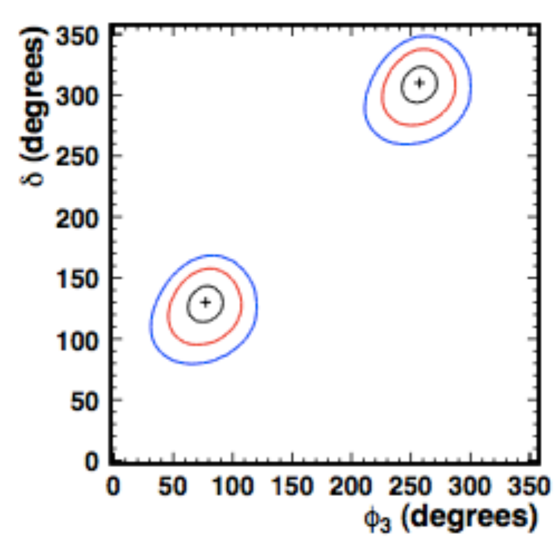
Simultaneous fit to kinematic information together with entries in each Dalitz bin.

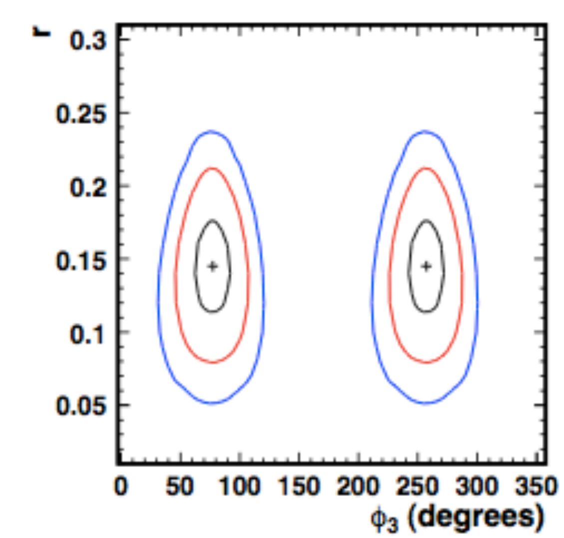
→ $x_{\pm} = r \cos(\pm\phi_3+\delta)$,

$y_{\pm} = r \sin(\pm\phi_3+\delta)$

from $B^{\pm}$



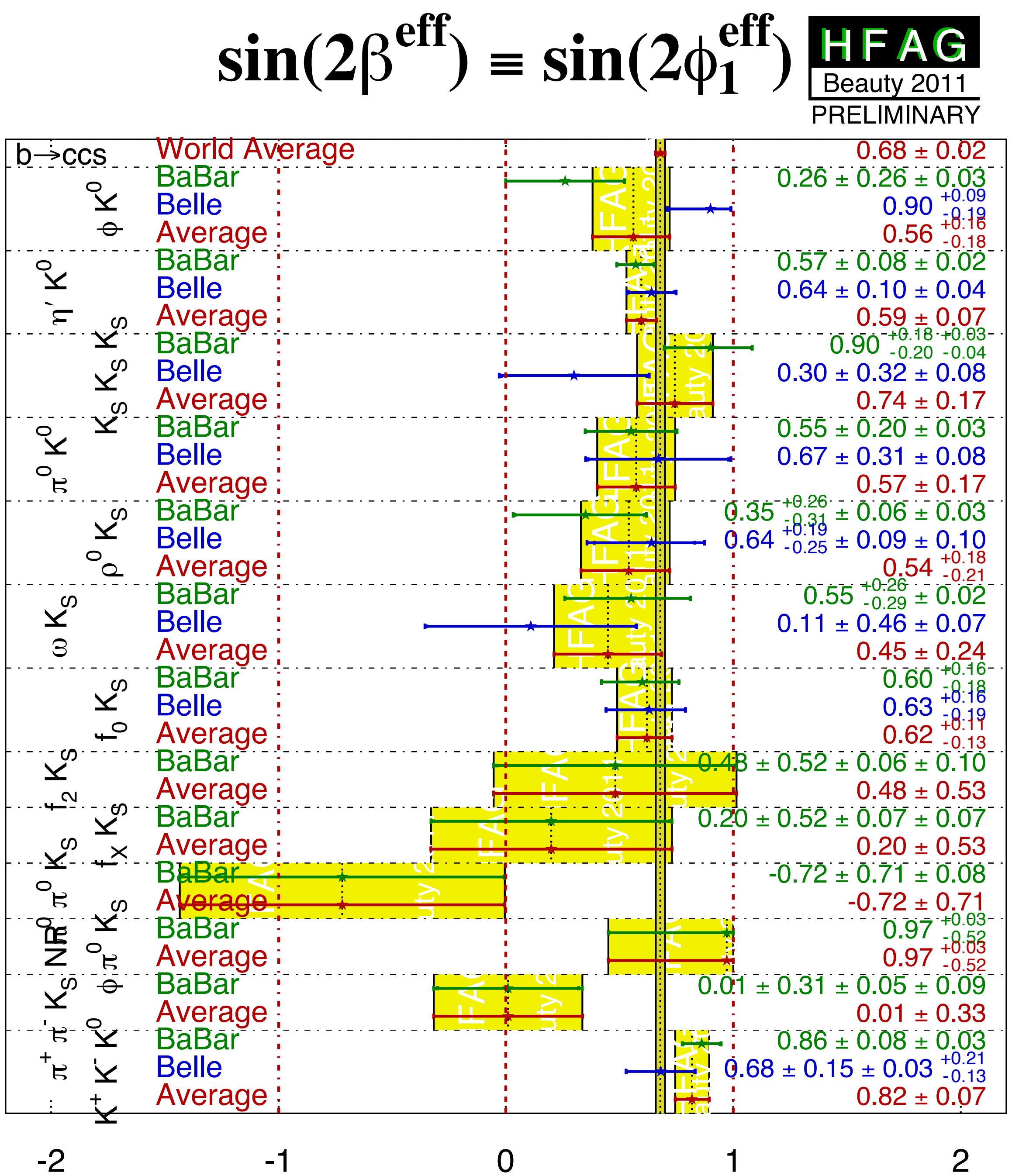


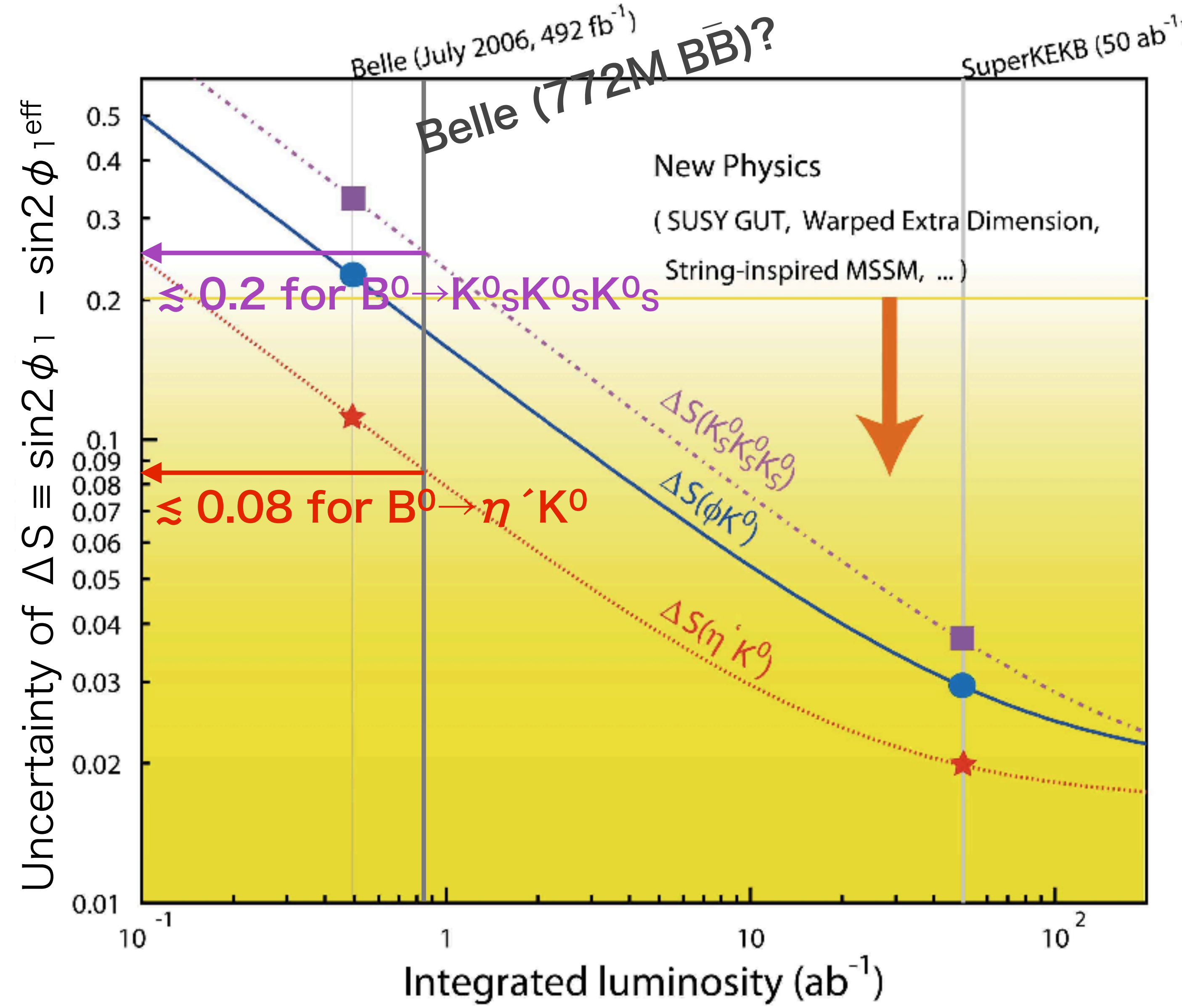


Prospects in short term

Common analysis variables for time-dependent CPV study has been ready (Δt resolution, B flavor wrong tagging…)

- $\sin 2\phi_1$ from b→s penguin (“effective” $\sin 2\phi_1 \equiv \sin 2\phi_1^{eff}$)





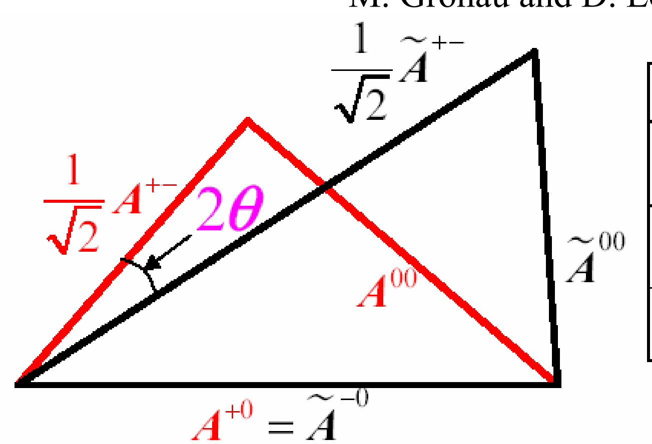
Prospects in short term

Common analysis variables for time-dependent CPV study has been ready (Δt resolution, B flavor wrong tagging…)

- Time-dependent analysis and branching fraction measurements of $B^0 \to \pi\pi$, $B^0 \to \rho\rho$ for iso-spin relation analysis of ϕ_2
- CP violation in $b \to c\bar{c}d$: $B^0 \to D^{(*)+}D^{(*)-}$

Interpretation: ϕ_2 constraint using isospin

M. Gronau and D. London, PRL 65, 3381 (1990)



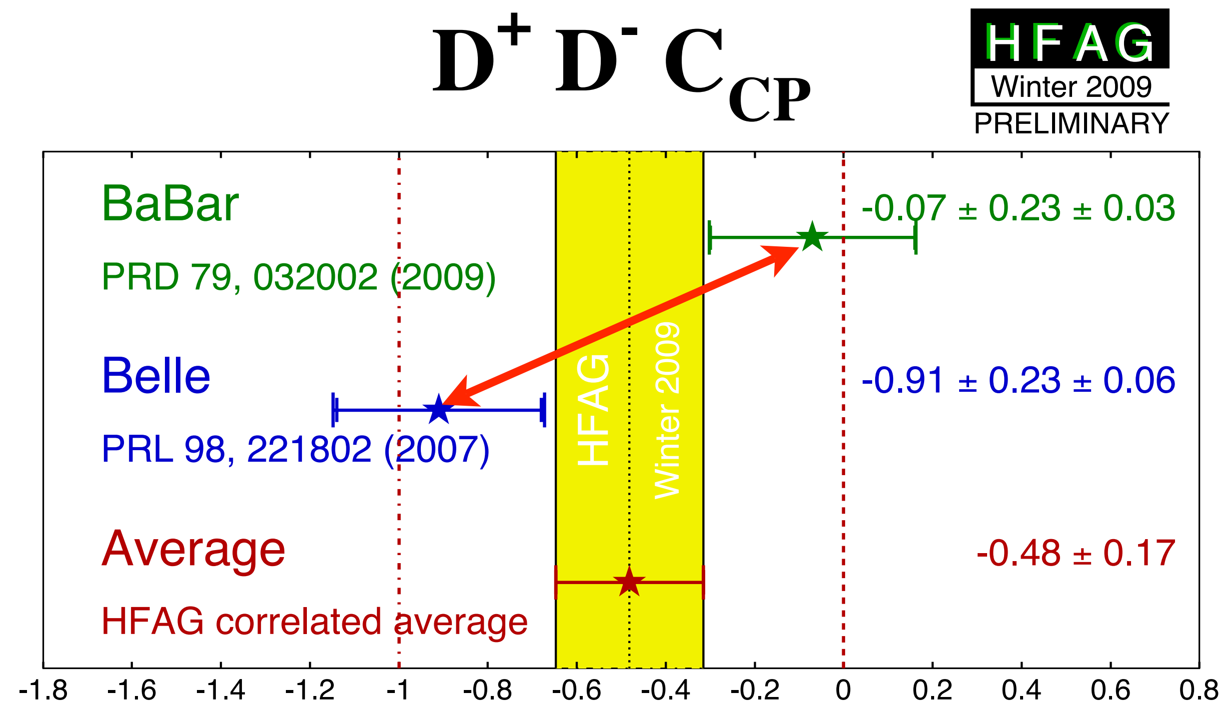
	Amplitude for
$A^{+-}(\overline{A}^{+-})$	$B^0(\overline{B}^0) \to \pi^+\pi^-$
$A^{00}(\overline{A}^{00})$	$B^0(\overline{B}^0) \to \pi^0\pi^0$
$A^{+0}(\overline{A}^{-0})$	$B^+(B^-) \to \pi^+\pi^0(\pi^-\pi^0)$

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

$$S_{\pi\pi} = \sqrt{1 - A_{\pi\pi}^2}\sin(2\phi_2 + 2\theta)$$

The cleanest method to extract ϕ_2

We use the statistical treatment of
J. Charles *et al.*, Eur. Phys. J. C 41, 1 (2005)



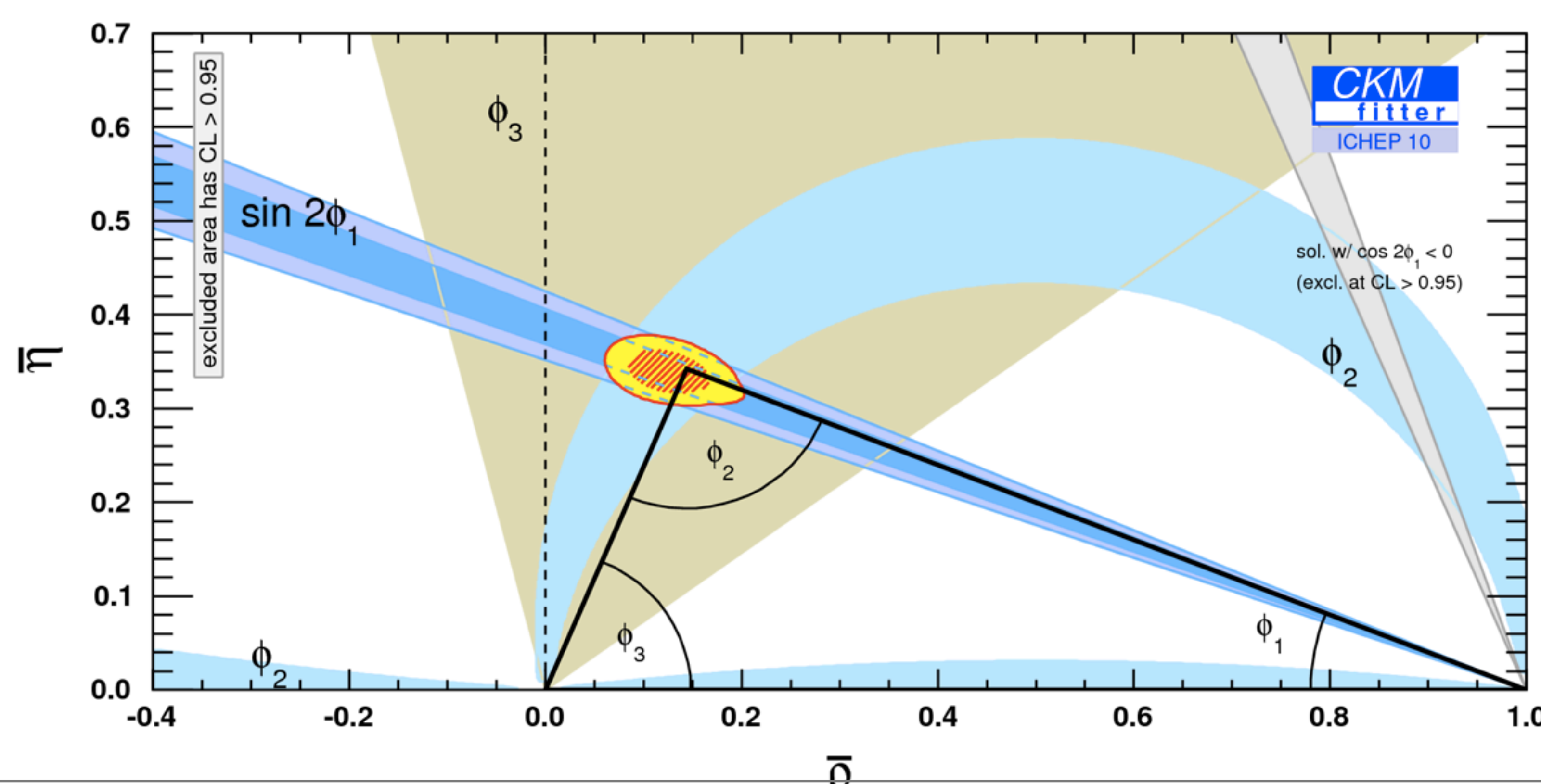
Belle observed direct CPV in $B^0 \to D^+\bar{D}^-$ decay using 535M$B\bar{B}$ → How about using full data?

Summary

- $\sin 2\phi_1 = 0.68 \pm 0.02$ is measured in B-factories.
  (→ good reference point of Standard Model)

- New technical approaches to ϕ_3 measurements using interference of $B^\pm \to DK^\pm$ decays.

- We expect soon all the results from Belle final data sample.



backup

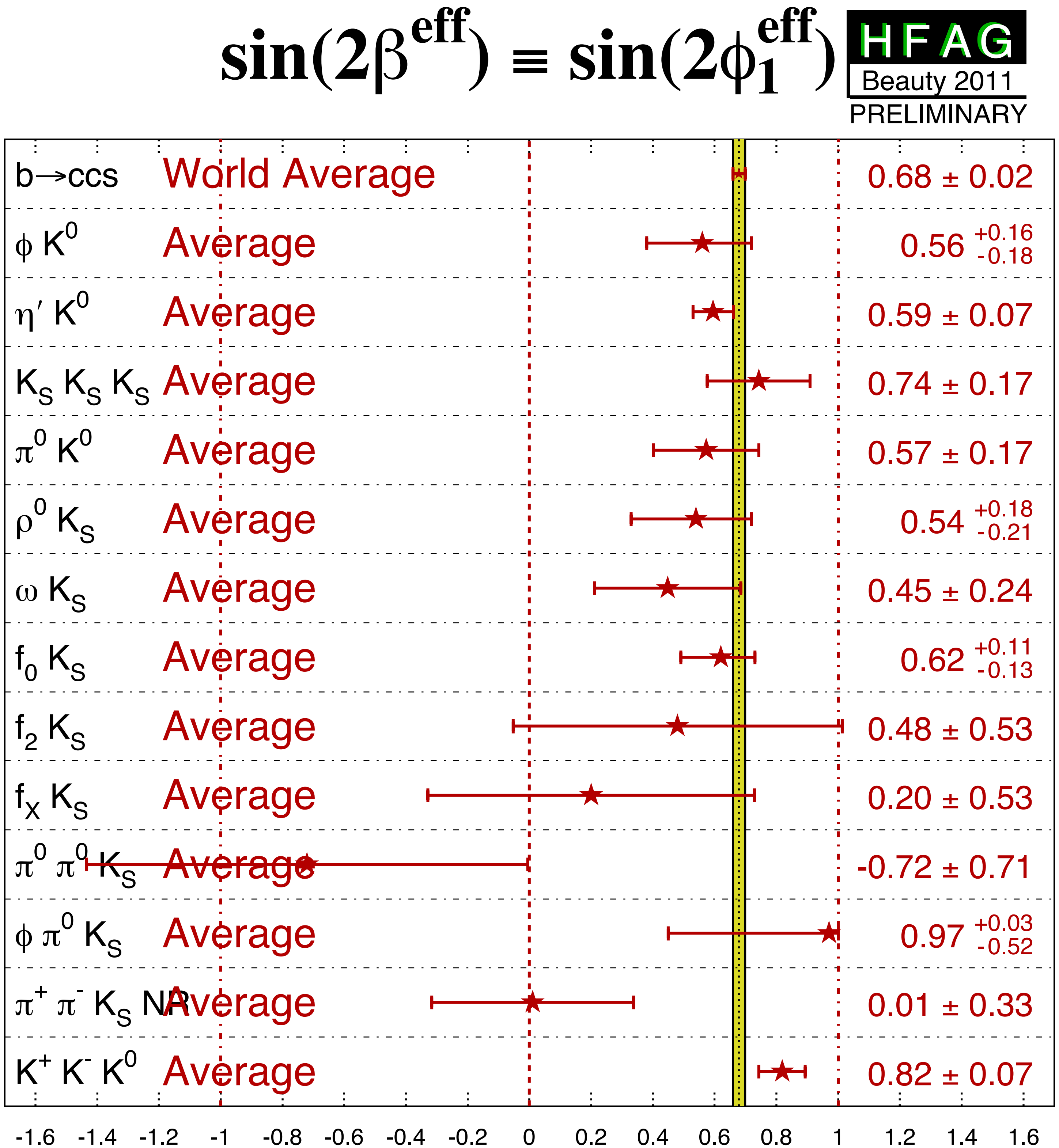
Systematic error of sin2ϕ_1

BELLE

	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/psiKs signal fraction	±0.002	±0.001
J/psiKL signal fraction	±0.004	+0.000/−0.002
psi2sKs signal fraction	<0.001	<0.001
chic1Ks signal fraction	<0.001	<0.001
Background Delta_t	±0.002	±0.001
Tag-side interference	±0.001	±0.008
Total	±0.013	±0.013

Source/sample		Full
Beam spot	S_f	0.001
	C_f	0.001
Mistag differences	S_f	0.006
	C_f	0.002
Δt resolution	S_f	0.007
	C_f	0.003
$J/\psi K^0_L$ background	S_f	0.006
	C_f	0.001
Background fraction and CP content	S_f	0.005
	C_f	0.003
m_{ES} parameterization	S_f	0.002
	C_f	0.000
$\Delta m_d, \tau_B, \Delta\Gamma_d/\Gamma_d$	S_f	0.003
	C_f	0.001
Tag-side interference	S_f	0.001
	C_f	0.014
Fit bias (MC statistics)	S_f	0.002
	C_f	0.003
Total	S_f	0.012
	C_f	0.016

$\sin 2\phi_1$ from $b \to s$ penguin



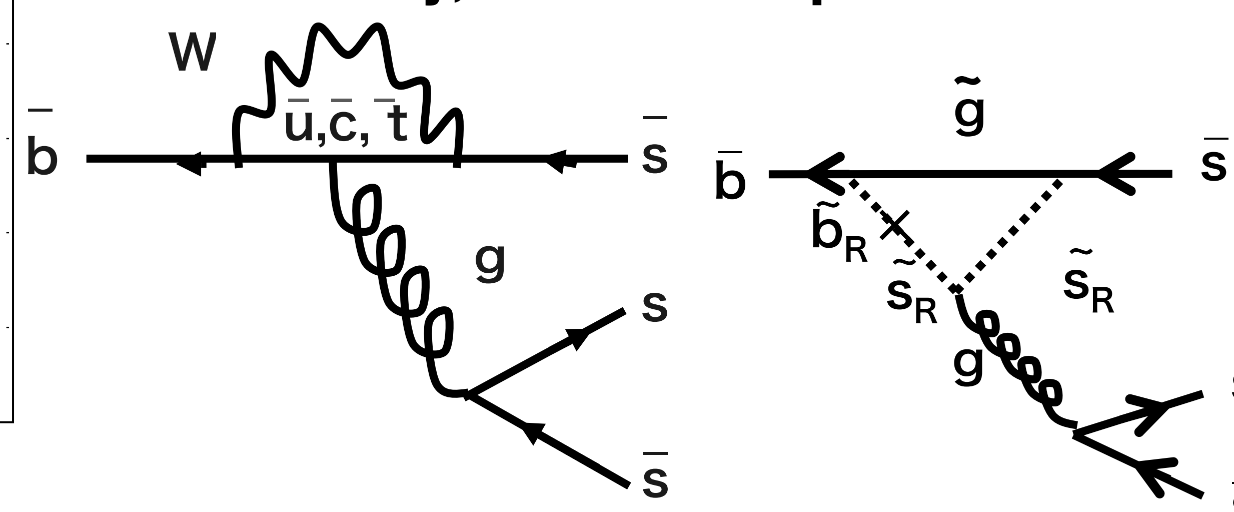
	ΔS
$B^0 \to \eta' K^0$	0.01 ± 0.01
$B^0 \to \phi K^0$	0.02 ± 0.01
$B^0 \to \omega K^0_S$	0.13 ± 0.08
$B^0 \to \rho^0 K^0_S$	$-0.08^{+0.08}_{-0.12}$
$B^0 \to K^0_S \pi^0$	$0.07^{+0.05}_{-0.04}$

J. Zupan, hep-ph/0707.1323

	ΔS
$B^0 \to K^+ K^- K^0_S$	$0.03^{+0.02}_{-0.03}$
$B^0 \to K^0_S K^0_S K^0_S$	$0.02^{+0.02}_{-0.03}$
$B^0 \to K^0_S \pi^0 \pi^0$	$0.03^{+0.02}_{-0.03}$

Hai-Yang Cheng, hep-ph/0702252

Generally, $\Delta S > 0$ is expected in SM



Model uncertainty of ϕ_3 Dalitz analysis

TABLE VI: Estimation of the $\overline{D}^0 \to K_S^0\pi^+\pi^-$ decay model uncertainty.

Fit model	$(\Delta r)_{\max}$	$(\Delta\phi_3)_{\max}$ (°)	$(\Delta\delta)_{\max}$ (°)
$F_r = F_D = 1$	0.01	3.1	3.3
$\Gamma(q^2) = \text{constant}$	0.02	4.7	9.0
$K^*(892)^+$, ρ, ω, $K^*(892)^-$, $f_0(980)$, $K_0^*(1430)$, non-res.	0.05	8.5	22.9
No σ_1	0.01	2.6	4.3
No σ_2	0.01	0.6	0.7
CLEO model	0.02	5.7	8.7

Source	x_-	y_-	x_+	y_+	x_-^*	y_-^*	x_+^*	y_+^*	x_{s-}	y_{s-}	x_{s+}	y_{s+}
Mass and width of Breit-Wigner's	0.001	0.001	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.002	0.001	0.002
$\pi\pi$ S-wave parameterization	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.002
$K\pi$ S-wave parameterization	0.001	0.004	0.003	0.008	0.001	0.006	0.002	0.004	0.003	0.002	0.003	0.007
Angular dependence	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.002	0.002	0.001	0.002	0.001
Blatt-Weisskopf radius	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001
Add/remove resonances	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.002
DP efficiency	0.003	0.002	0.003	0.001	0.001	0.001	0.001	0.001	0.004	0.002	0.003	0.001
Background DP shape	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Mistag rate	0.003	0.003	0.002	0.001	0.001	0.001	0.001	0.001	0.003	0.003	0.001	0.001
Effect of mixing	0.003	0.001	0.003	0.001	0.001	0.001	0.001	0.001	0.003	0.001	0.003	0.001
DP complex amplitudes	0.001	0.001	0.001	0.002	0.001	0.001	0.001	0.002	0.002	0.001	0.001	0.002
Total D^0 decay amplitude model	0.006	0.006	0.007	0.009	0.002	0.007	0.003	0.006	0.007	0.006	0.006	0.008

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