CP Violation at Belle

Christoph Schwanda
Institute of High Energy Physics
Austrian Academy of Sciences

EXA2011

International Conference on Exotic Atoms and Related Topics
September 5-9, 2011, Vienna, Autria

CP violation…

- CP is the combination of charge-conjugation (C) and parity (P)
- CP found to be violated in 1964 neutral kaon decays (Fitch, Cronin)

$$e_{\mathrm{L}}^{-} \xrightarrow{C} e_{\mathrm{L}}^{+} \xrightarrow{P} e_{\mathrm{R}}^{+}$$

… in the Standard Model

- W couples to the isospin rather than to the flavor eigenstates (quark mixing)
- 3-generation quark mixing introduces a non-trivial complex phase (Kobayashi, Maskawa, 1973)
- All CP violation in the SM generated by this single parameter

→ strongly constrained pattern of CP violating effects

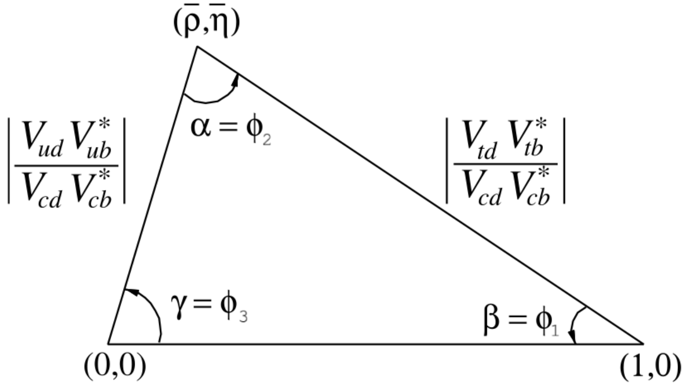
Charged current

$$-\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}} \overline{u_{Li}} \, \gamma^\mu$$

$$(V_{\mathrm{CKM}})_{ij} \, d_{Lj} \, W_\mu^+ + \mathrm{h.c.}$$

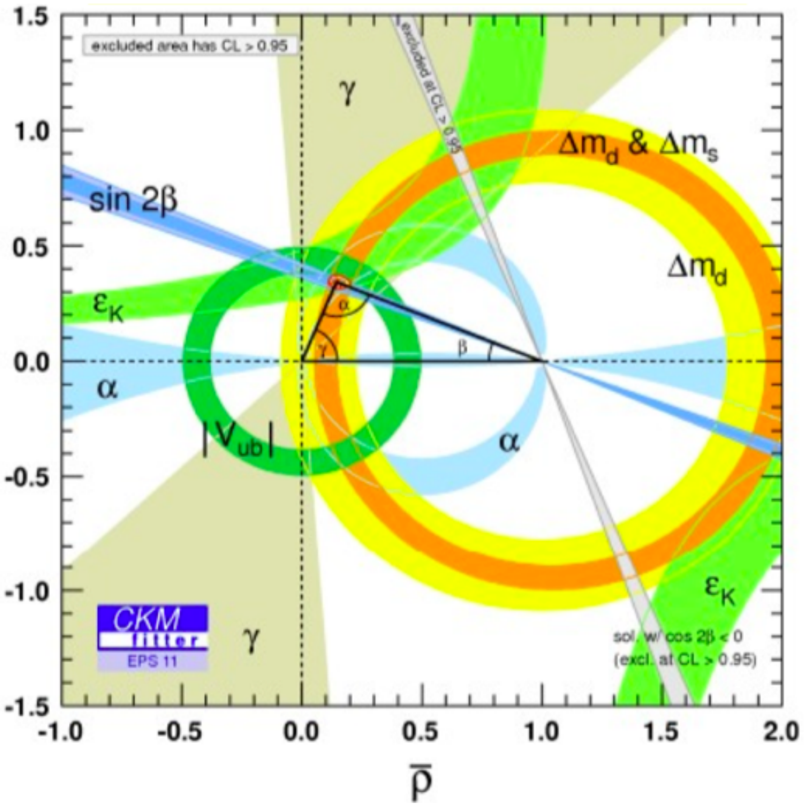
$$\begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

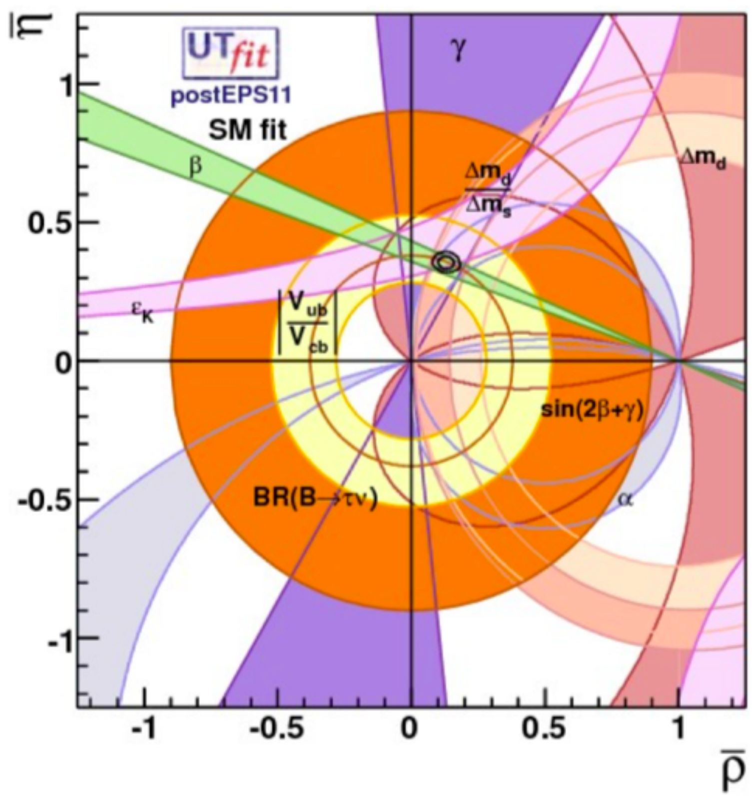
Probing the SM pattern of CP violation



$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{td}^* = 0$$

- Different processes put constraints on the unitarity triangle
- The most stringent ones come from the B meson decays: Belle can measure the angles (ϕ_1, ϕ_2, ϕ_3) and the sides ($|V_{cb}|$ and $|V_{ub}|$) of the UT

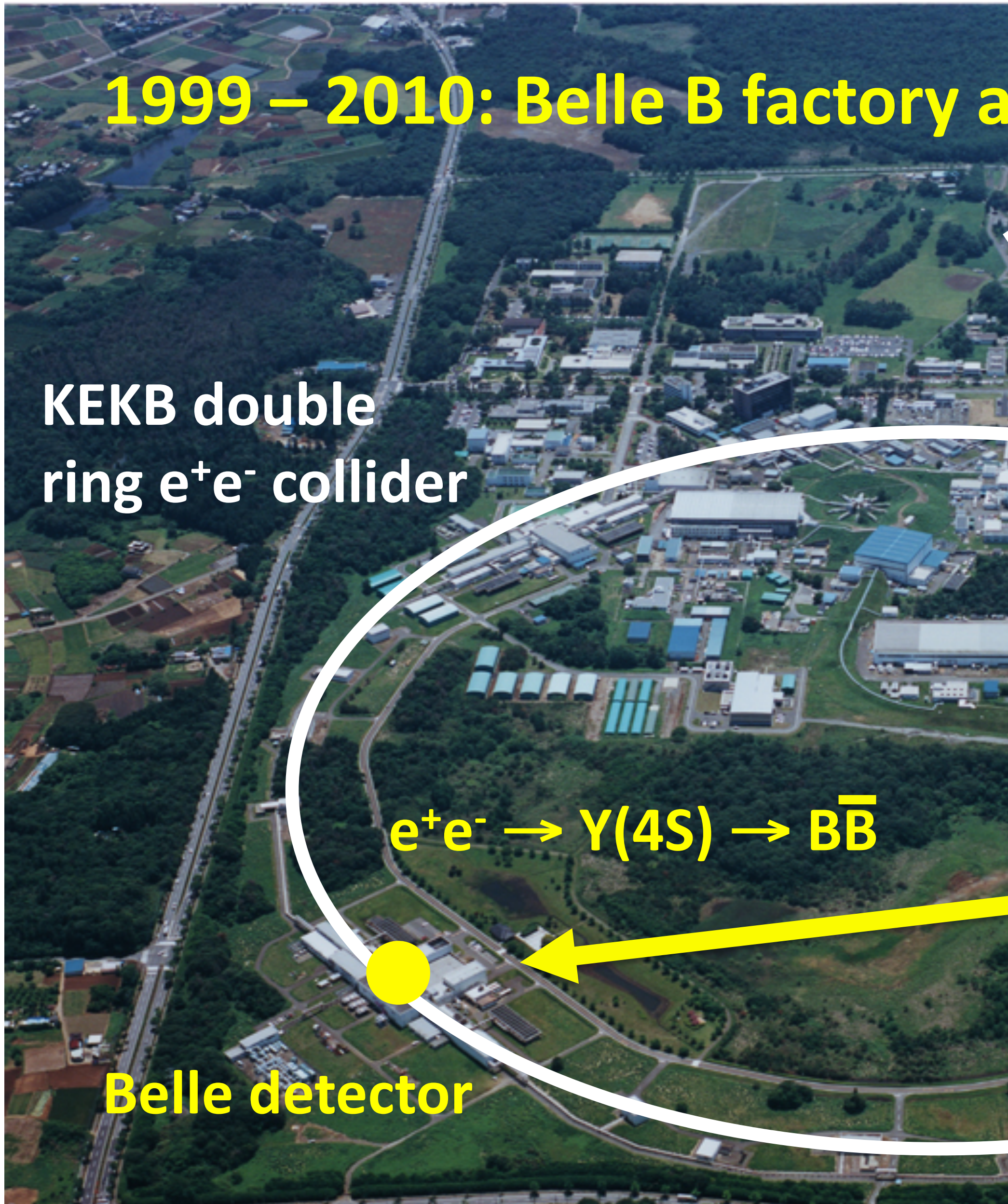


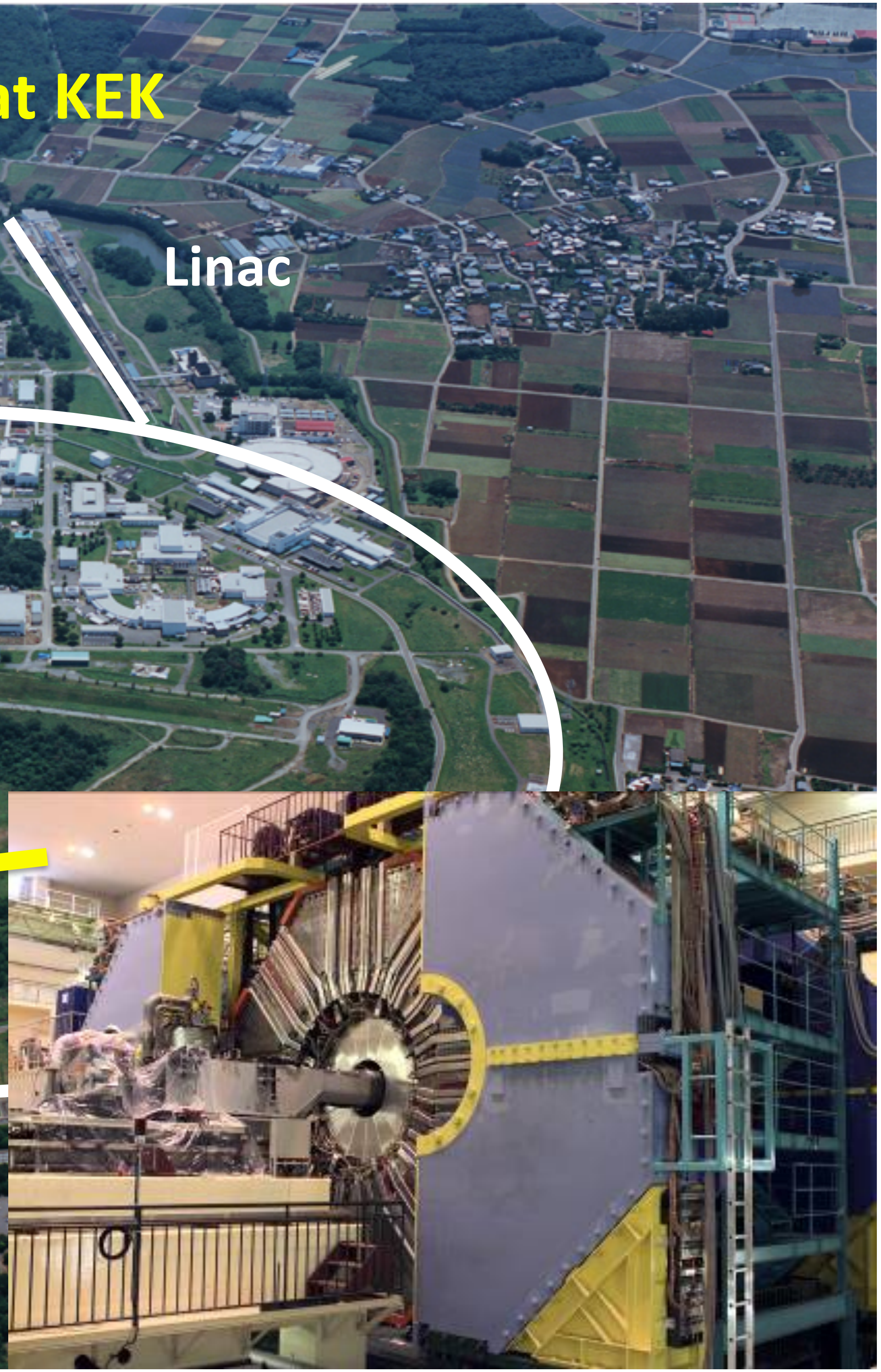


UT observables from B decays

Observable	Measurement	Recent Belle results
ϕ_1	Mixing-induced CPV in $B^0 \to (c\bar{c})\, K^0$	- $B^0 \to (c\bar{c})\, K^0$ 711/fb [Winter 2011] - $B^0 \to D^{(*)+} D^{(*)-}$ 711/fb [EPS 2011]
ϕ_2	Mixing-induced CPV in $B^0 \to \pi\pi, \rho\rho, \rho\pi$	
ϕ_3	Interference between $B^\pm \to \bar{D}\, K^\pm$ and $B^\pm \to D\, K^\pm$	- Binned Dalitz plot 711/fb [arXiv:1106.4046] - First evidence $B \to D\, K$ ADS 711/fb [PRL 106, 231803 (2011)] - $B \to D^*(D\pi^0, D\gamma)\, K$ ADS 711/fb [LP2011] - $B \to D_{CP}\, K$ GLW 711/fb [LP2011]
$\|V_{cb}\|$	$B \to X_c\, l\, \nu$	- $B^0 \to D^{*-}\, l^+\, \nu$ 711/fb [PRD 82, 112007 (2010)]
$\|V_{ub}\|$	$B \to X_u\, l\, \nu$	- $B^0 \to \pi^-\, l^+\, \nu$ 605/fb [PRD 83, 071101 (2011)]

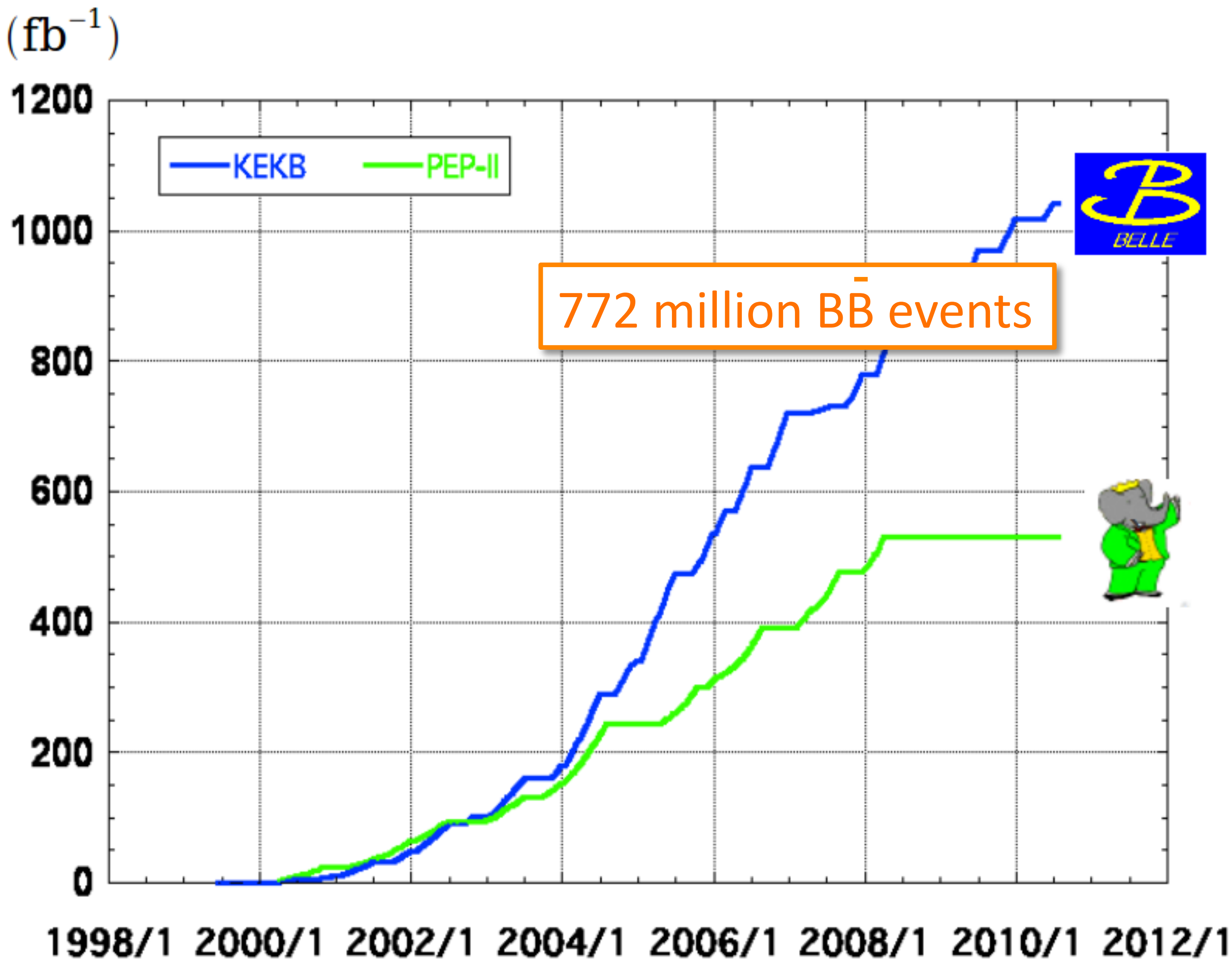
1999 – 2010: Belle B factory at KEK





- 3.5 GeV positrons on 8 GeV electrons
- E_{cm} = 10.58 GeV, $\beta\gamma$ = 0.425

Integrated luminosities of B factories



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

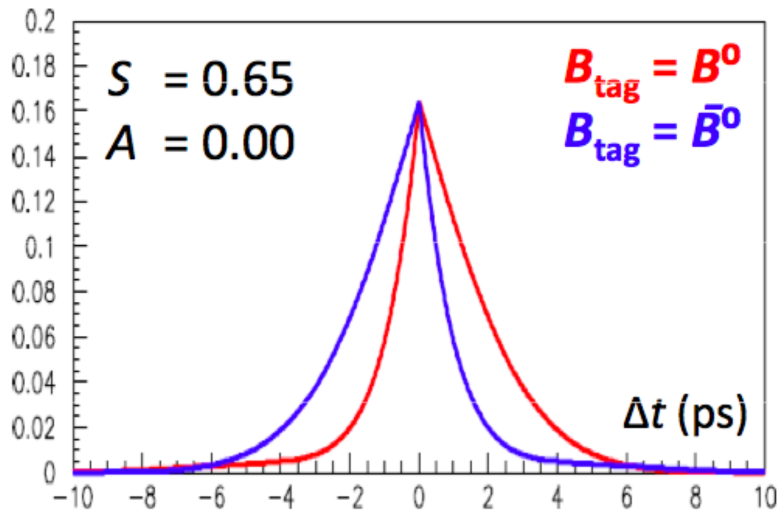
Mixing-induced CP violation

- $e^+e^- \to \Upsilon(4S) \to B^0_{CP}\, B^0_{tag}$
  - B^0_{CP} … B^0 decaying into CP eigenstate
  - B^0_{tag} … B^0 decaying into flavor-eigenstate (B^0 or $\bar{B}^0$)
- In case of mixing-induced CPV, the $\Delta t = t_{CP}-t_{tag}$ distributions are different for B^0 and $\bar{B}^0$ tags

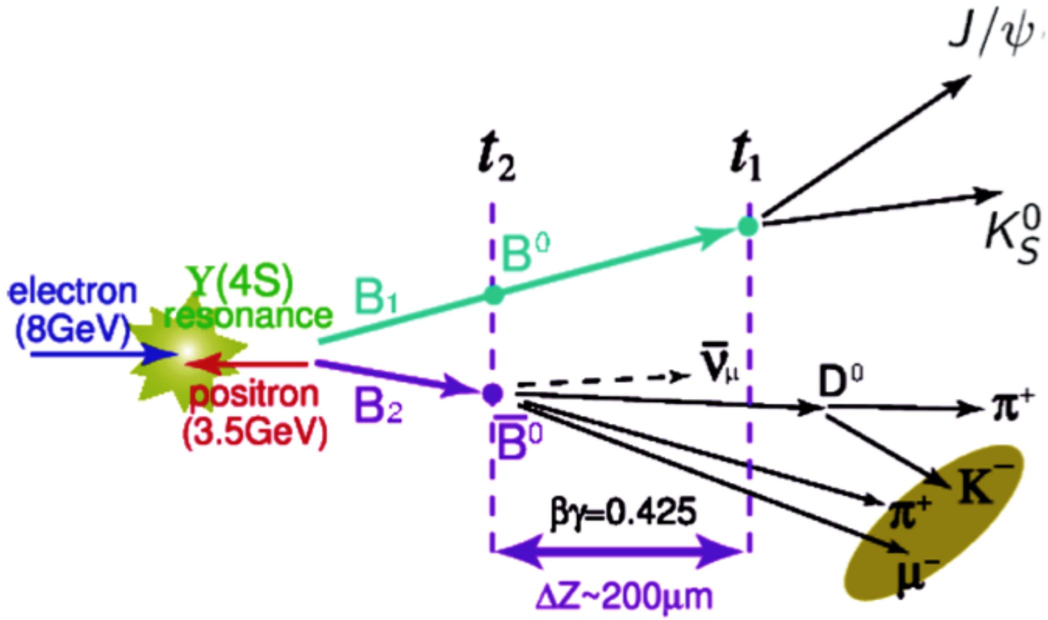
$$P_{\text{sig}}(\Delta t, q; S, A) = \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B}\left[1 + q\cdot(A\cos\Delta m_d \Delta t + S\sin\Delta m_d \Delta t)\right]$$

q = +1 for B^0 tag

q = -1 for $\bar{B}^0$ tag



Measuring CPV



- The decay time difference Δt is inferred from decay vertex difference Δz and the known boost βγ of the center-of-mass frame

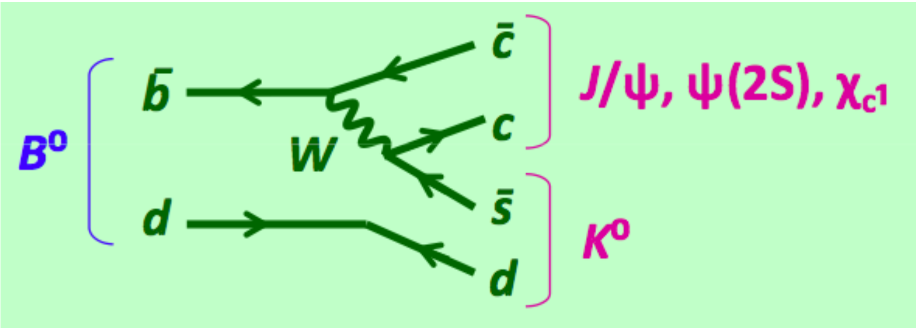
CPV in $B^0 \to (c\bar{c})K^0$ and $D^{(*)+}D^{(*)-}$

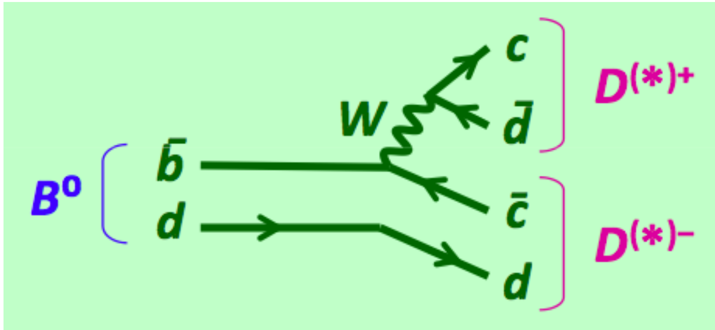
$B^0 \to (c\bar{c})\ K^0$

$b \to c\bar{c}s$ tree transition

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

$b \to c\bar{c}d$ tree transition

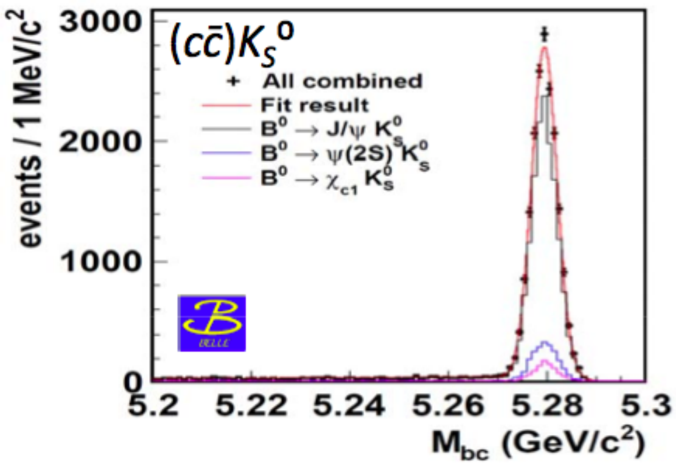


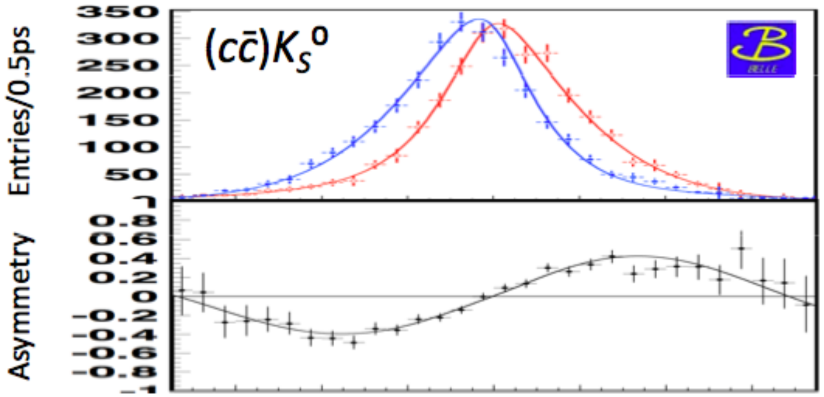


- Both decays mainly mediated by the tree diagram
- SM prediction: $S = -\eta_{CP} \sin 2\phi_1$, $A \approx 0$ (η_{CP} ... CP eigenvalue)
- $\phi_1 = \mathrm{Arg}(V_{cd}V^*_{cb}/V_{td}V^*_{tb})$

CPV in $B^0 \to (c\bar{c})\ K^0$

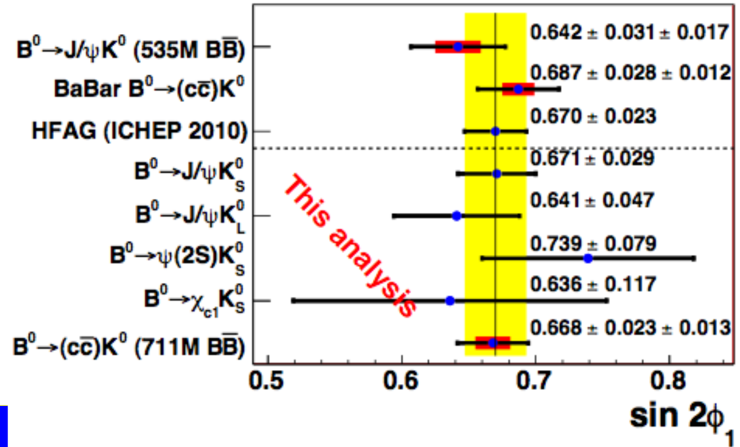
772M BB (final dataset)





$B_{tag} = B^0$

$B_{tag} = \bar{B}^0$



$CP = -1$ 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

$$S = 0.668 \pm 0.023 \pm 0.013\ (\text{syst})$$

$$A = 0.007 \pm 0.016 \pm 0.013\ (\text{syst})$$

sin $2\phi_1$

CPV in $B^0 \to D^+D^-$

Belle preliminary

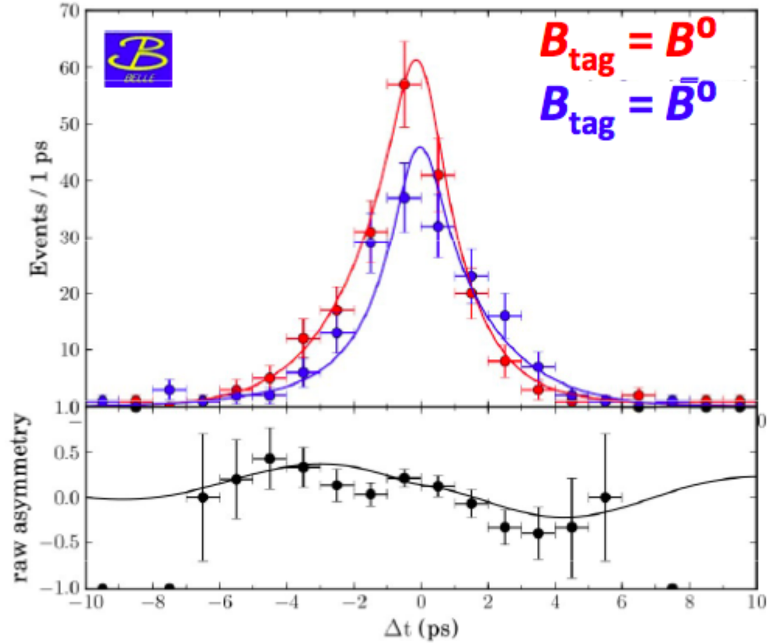
772M BB (final dataset)

$$S = -1.06 \pm 0.21 \pm 0.07$$

$$A = +0.43 \pm 0.17 \pm 0.04$$

772×10^6 $B\bar{B}$ pairs

$B^0 \to (K^-\pi^+\pi^+)(K^+\pi^-\pi^-)$, $(K^-\pi^+\pi^+)(K_S\pi^0)$+c.c.



CPV in $B^0 \to D^{*+}D^{*-}$

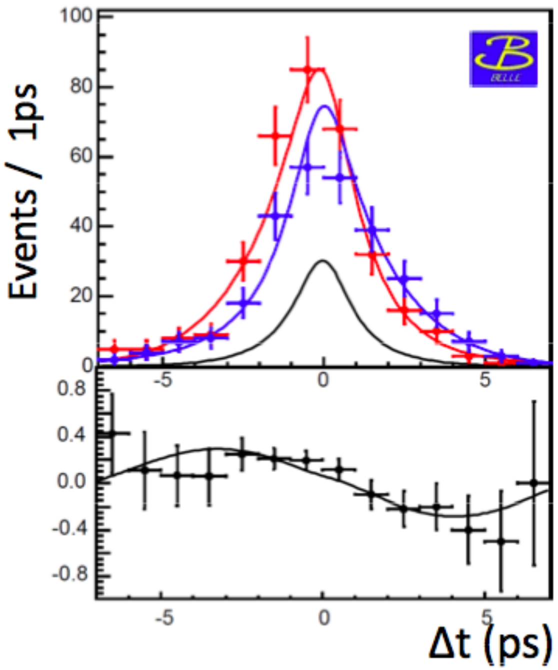
$$S = -0.79 \pm 0.13 \pm 0.03$$

$$A = +0.15 \pm 0.08 \pm 0.02$$

$$R_0 = 0.62 \pm 0.03 \pm 0.01$$

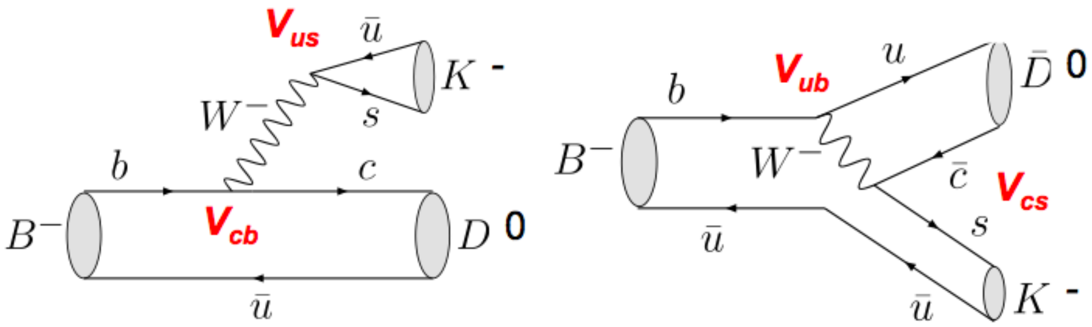
$$R_\perp = 0.14 \pm 0.02 \pm 0.01$$

772×10^6 $B\bar{B}$ pairs



- Angular analysis needed to access CPV in $B^0 \to$ VV decay

Measurement of ϕ_3

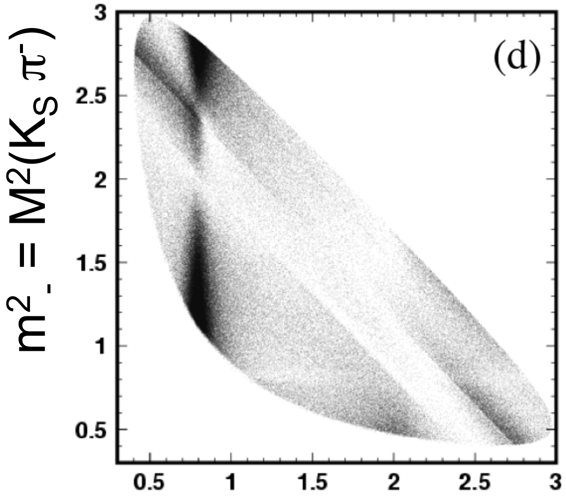


- If D^0 and $\bar{D}^0$ decay to the same final state, both diagrams contribute to the observed rate

- The subsequent interference allows to determine the relative phase between these diagrams $\delta \pm \phi_3$, $\phi_3 = \mathrm{Arg}(V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$
- 3 approaches
  - Gronau-London-Wyler (GLW): uses D^0 decays to a CP eigenstate
  - Atwood-Dunietz-Soni (ADS): uses Cabibbo-favored and doubly-Cabibbo-suppressed D^0 modes
  - Dalitz plot analysis: uses three-body decays, e.g., $D^0 \rightarrow K_S\, \pi^+ \pi^-$

ϕ_3 with a Dalitz plot analysis
Giri, Grossman, Soffer, Zupan [PRD 68, 054018 (2003)]

$D^0 \to K_S \pi^+ \pi^-$ Dalitz plot



$m^2_+ = M^2(K_S \pi^+)$

- Amplitude M_+ of $B^+ \to D(K_S \pi^+ \pi^-) K^+$
  $M_+ = A(m^2_+, m^2_-) + re^{i(\delta+\phi 3)} A(m^2_-, m^2_+)$
- Amplitude M_- of $B^- \to D(K_S \pi^+ \pi^-) K^-$
  $M_- = A(m^2_-, m^2_+) + re^{i(\delta-\phi 3)} A(m^2_+, m^2_-)$
- $r = A(B \to DK) / A(B \to \bar{D}K)$

$B^{+/-}$ Dalitz plot density:

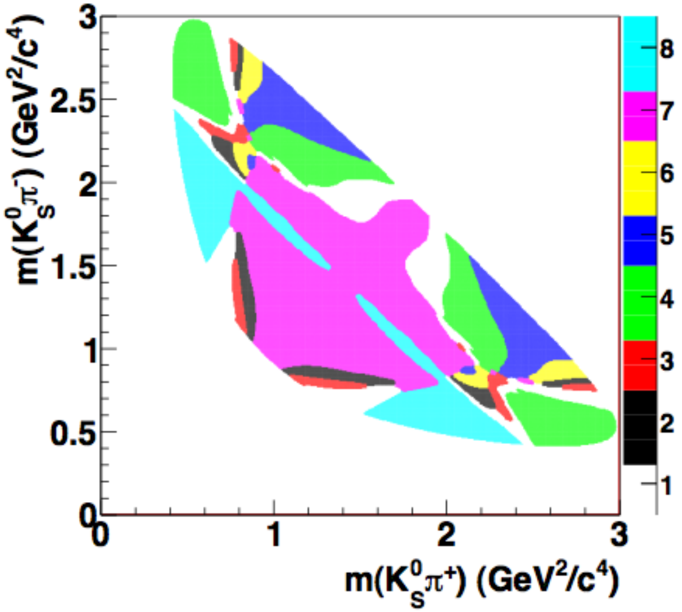
$$\left|M_\pm\right|^2 = (r^2)_- \left|A(m_+^2, m_-^2)\right|^2 + (r^2)_+ \left|A(m_-^2, m_+^2)\right|^2 + 2\left|A(m_+^2, m_-^2)\right|\left|A(m_-^2, m_+^2)\right| r \cos(\delta + \theta_{(m_+^2, m_-^2)} \pm \phi_3)$$

D related strong phase difference (model-dependent!)

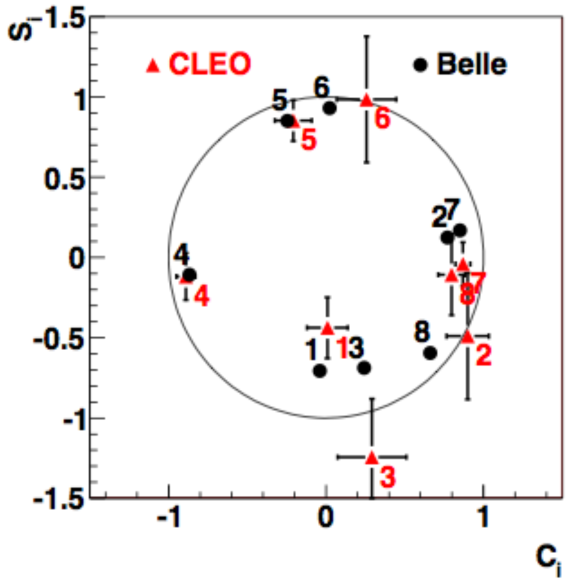
Binned Dalitz plot analysis

- Measure the D related strong phase difference at CLEO-c in $\psi(3770) \to DD$ events [PRD 82, 112006 (2010)]
- Convert model into experimental error

Optimal binning (8 bins)



CLEO measurement compared to Belle model

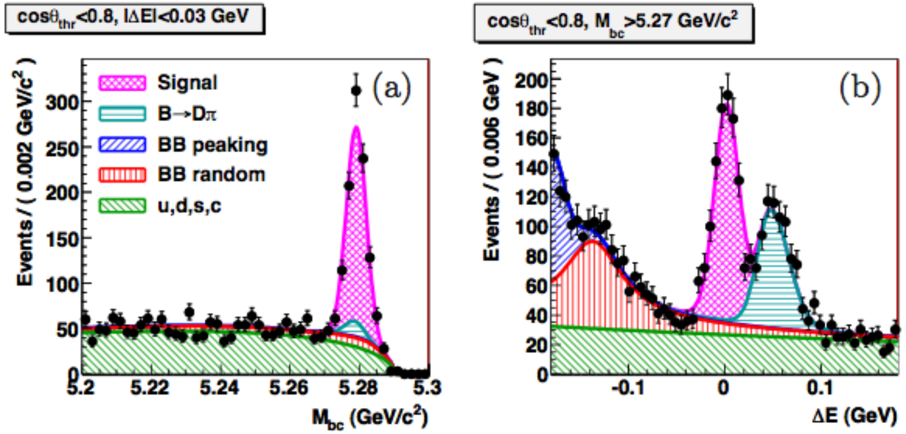


Belle ϕ_3 measurement using binned Dalitz plot analysis

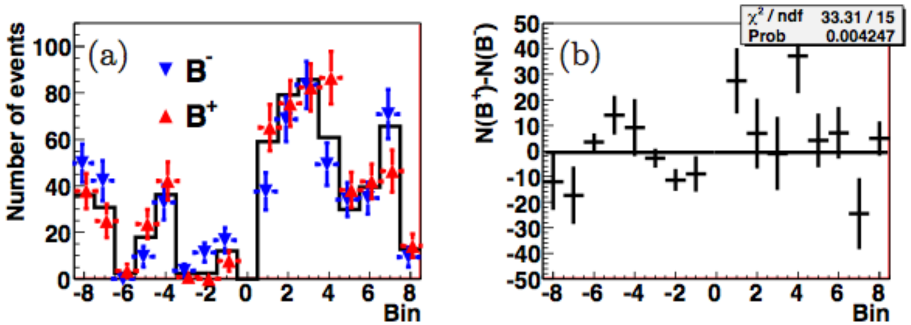
Belle preliminary

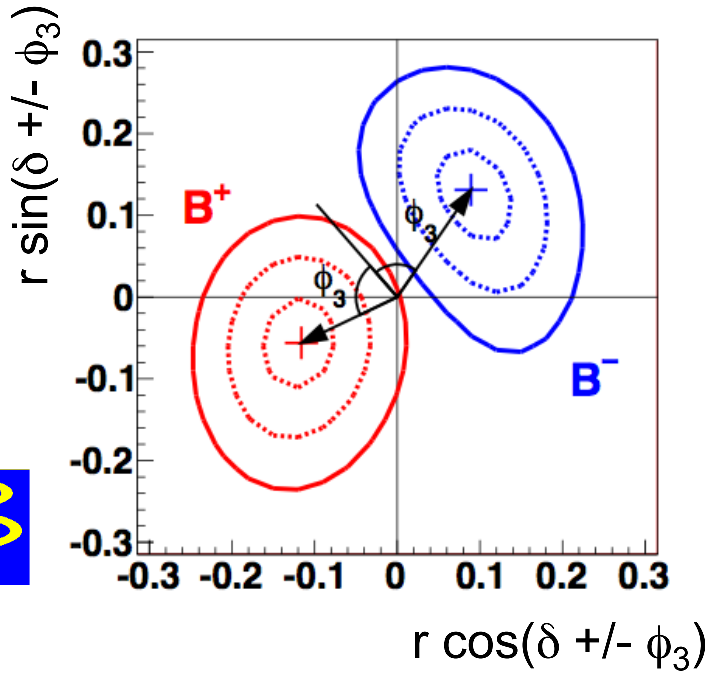
772M BB (final dataset)

1176 +/- 43 evts $B \to D(K_S\pi^+\pi^-)$ K



Difference $B^{+/-}$

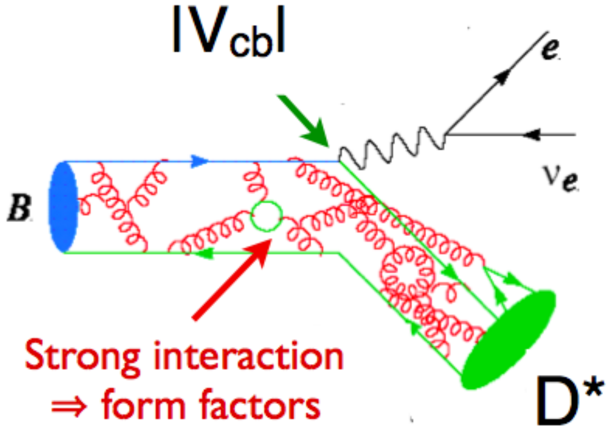


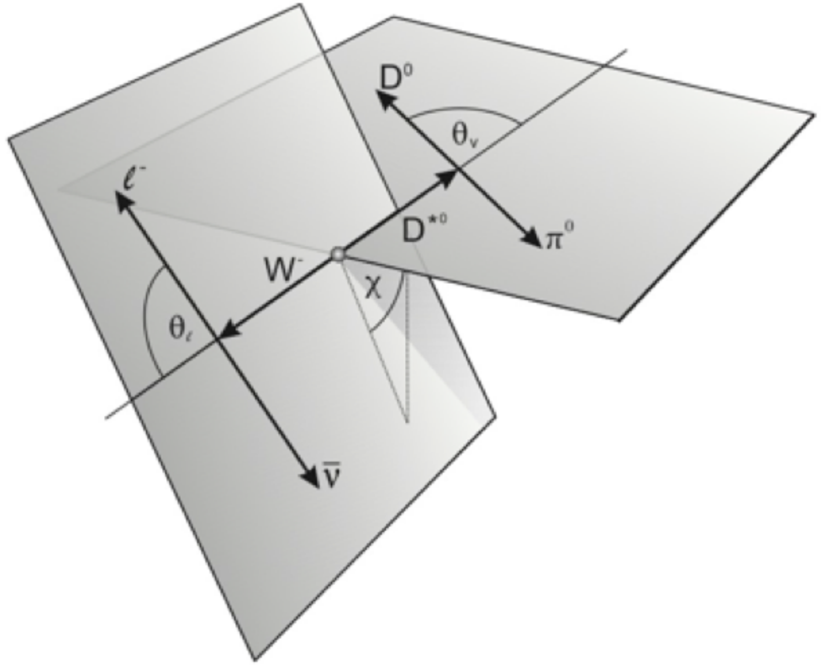


$\phi_3=(77.3^{+15.1}_{-14.9} \pm 4.2 \pm 4.3(c_i,s_i))^\circ$
$r_B=0.145 \pm 0.030 \pm 0.011 \pm 0.011$
$\delta_B=(129.9 \pm 15.0 \pm 3.9 \pm 4.7)^\circ$

- Belle model-dependent result [PRD 81, 112002 (2010)]: ϕ_3 = (78 +/- 11 +/- 4 +/- 9(model))°

$|V_{cb}|$ from exclusive decays: $B \to D^* l\nu$





$$\frac{d\Gamma(B \to D^*\ell\nu)}{dw\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} = \frac{G_F^2}{48\pi^3}|V_{cb}|^2 m_{D^*}^3 (w^2-1)^{1/2} P(w)\mathcal{F}(w,\ldots)^2$$

$$\mathcal{F}(w) \Rightarrow \mathcal{F}(w, \cos\theta_\ell, \cos\theta_V, \chi, R_1, R_2, \rho^2)$$

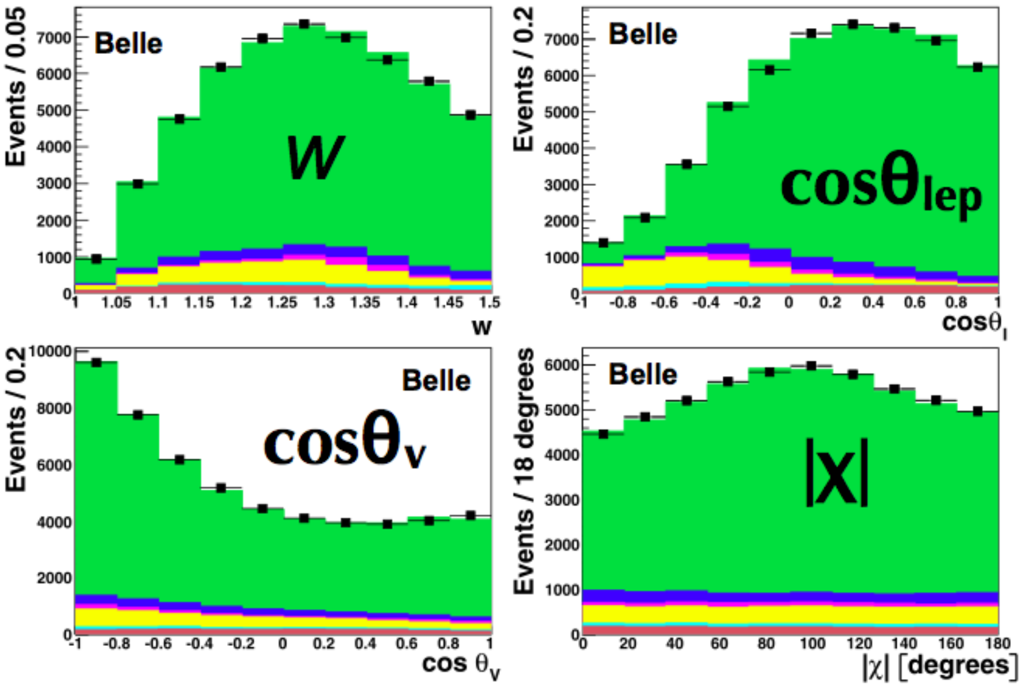
$$w \equiv v_B \cdot v_{D^{(*)}} = \frac{p_B \cdot p_{D^{(*)}}}{m_B \cdot m_{D^{(*)}}} : D^{(*)} \text{ boost}$$

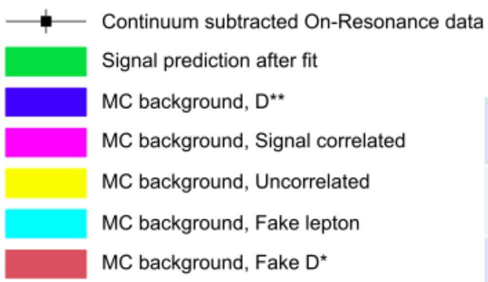
- Form factor shape parameterized by ρ^2, R_1, R_2
- Form factor normalization F(1) must be taken from lattice QCD: F(1) = 0.908 +/- 0.017 [PoS Lattice 2010:311 (2010)]

Belle $B^0 \to D^{*-} l^+ \nu$

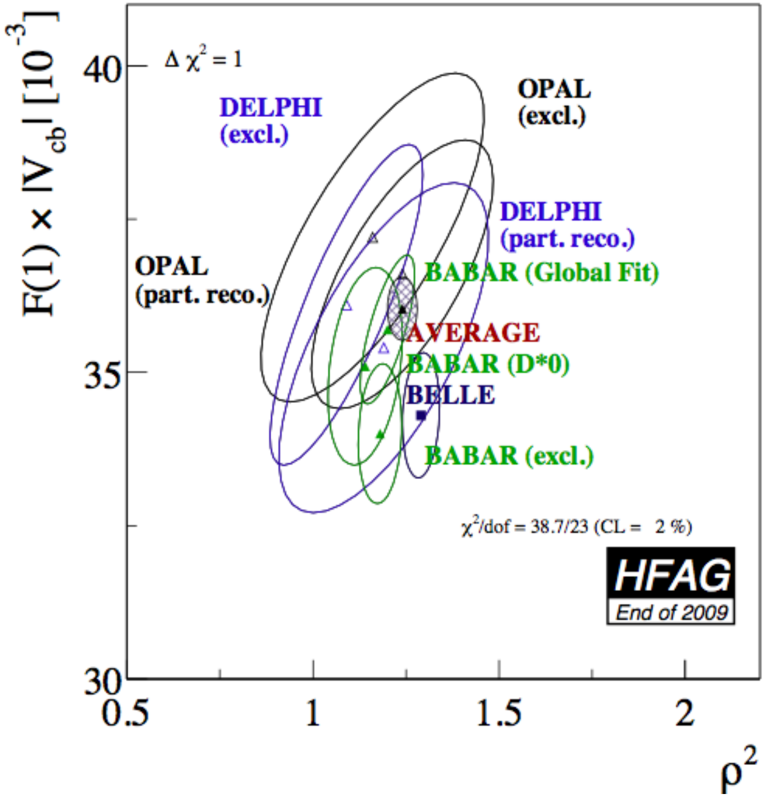
[PRD 82, 112007 (2010)]

772M BB (final dataset)





ρ^2	1.214±0.034±0.009
$R_1(1)$	1.401±0.034±0.018
$R_2(1)$	0.864±0.024±0.008
$BR(\%)$	4.58±0.03±0.26
$F(1)\lvert V_{cb}\rvert$	34.6±0.2±1.0
χ^2/dof	138.8/155

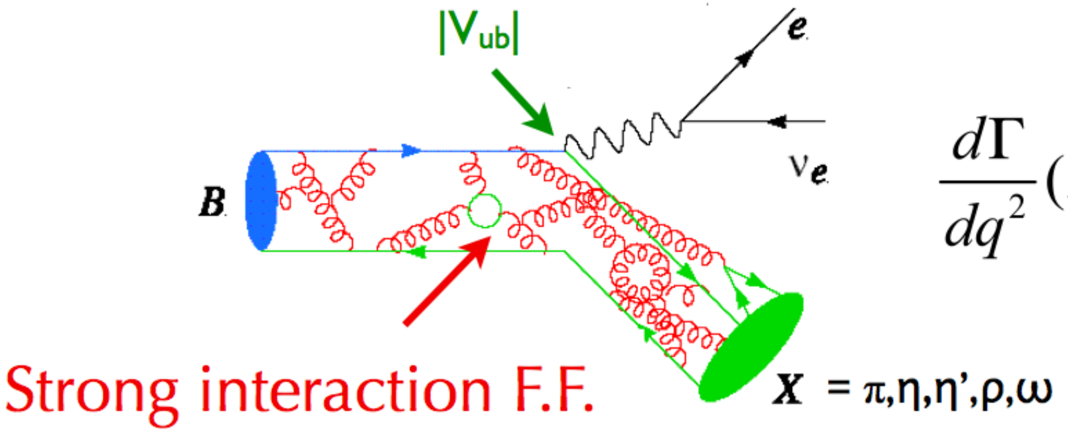


⇨Belle
$|V_{cb}| = (38.0 \pm 0.2 \pm 1.1 \pm 0.7(FF))\ 10^{-3}$

Belle $|V_{ub}|$ from $B^0 \to \pi^- l^+ \nu$

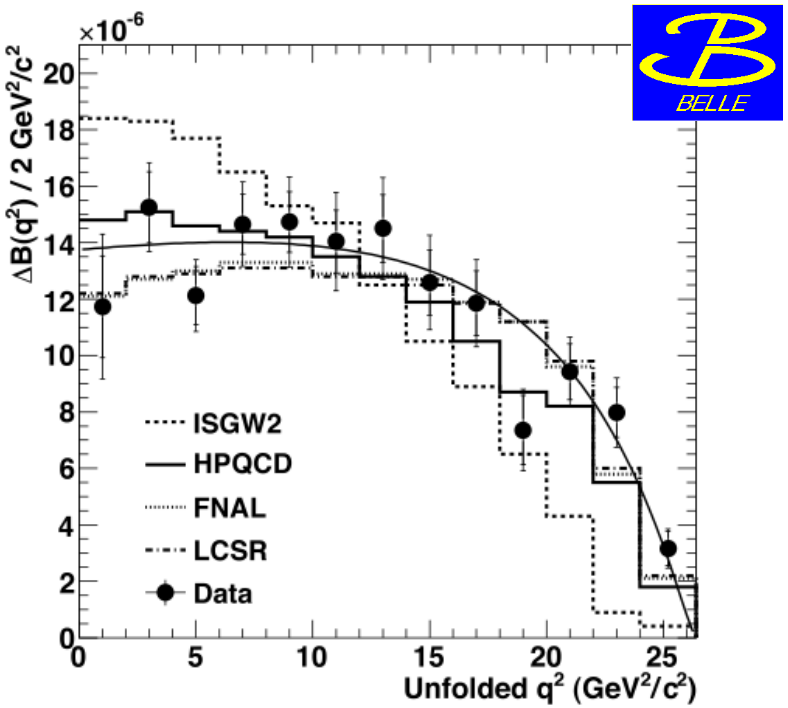
[PRD 83, 071101(R) (2011)]

657M BB



$$\frac{d\Gamma}{dq^2}(B \to \pi l \nu) = \frac{G_F^2}{24\pi^3} p_\pi^3 |V_{ub}|^2 |f_+(q^2)|^2$$

$$q^2 = (p_\ell + p_\nu)^2 = (p_B - p_\pi)^2$$



- Combined fit with FNAL/MILC lattice data [PRD 79, 054507 (2009)] to reduce form factor uncertainty
- $Br(B^0 \to \pi^- l^+ \nu) = (1.49 +/- 0.04 +/- 0.07) \times 10^{-4}$
- $|V_{ub}| = (3.43 +/- 0.33) \times 10^{-3}$

Summary and conclusion

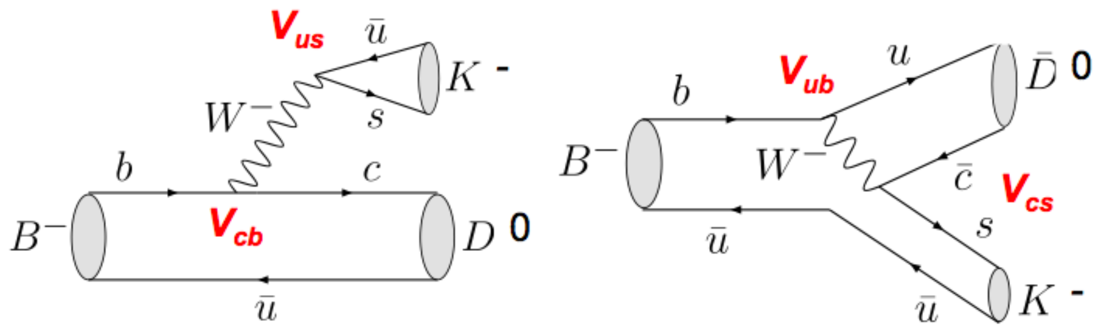
- The pattern of CP violation in the Standard Model (SM) is strongly constrained
  (Cabibbo-Kobayahi-Maskawa mechanism -- CKM)
- Belle has tested if this pattern occurs through overconstraining the CKM unitarity triangle (UT)
- Despite some tensions in the UT fits, the SM is confirmed and the CKM mechanism holds
- The next generation of flavor physics experiments will improve precision and might see clear deviations from the CKM picture due to physics beyond the SM

Backup

Gronau-London-Wyler method

[PLB 253, 483 (1991); PLB 265, 172 (1991); PRD 58, 037301 (1998); PLB 557, 198 (2003)]

- Common mode is D^0 decay to CP eigenstate (CP even, odd), e.g., $D^0 \rightarrow K^+K^-$, $K^0{}_S\pi^0$
- Relative phase: $\delta+\phi_3$ (B^+) or $\delta-\phi_3$ (B^-)



$$R_+ \equiv \frac{2\left[B(B^-\to D_{CP+}K^-)+B(B^+\to D_{CP+}K^+)\right]}{B(B^-\to D^0K^-)+B(B^+\to \overline{D}{}^0K^+)} = 1+r^2+2r\cos\delta\cos\varphi_3$$

$$R_- \equiv \frac{2\left[B(B^-\to D_{CP-}K^-)+B(B^+\to D_{CP-}K^+)\right]}{B(B^-\to D^0K^-)+B(B^+\to \overline{D}{}^0K^+)} = 1+r^2-2r\cos\delta\cos\varphi_3$$

$$A_+ \equiv \frac{B(B^-\to D_{CP+}K^-)-B(B^+\to D_{CP+}K^+)}{B(B^-\to D_{CP+}K^-)+B(B^+\to D_{CP+}K^+)} = \frac{2r\sin\delta\sin\varphi_3}{R_+}$$

$$A_- \equiv \frac{B(B^-\to D_{CP-}K^-)-B(B^+\to D_{CP-}K^+)}{B(B^-\to D_{CP-}K^-)+B(B^+\to D_{CP-}K^+)} = \frac{-2r\sin\delta\sin\varphi_3}{R_-}$$

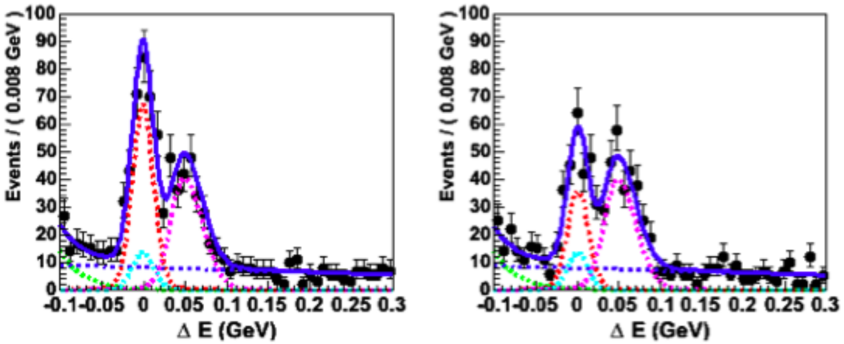
- Measure 6 rates
- Compute 4 observables
- Determine 3 unknown (r, δ, ϕ_3)

GLW measurement at Belle

Belle preliminary

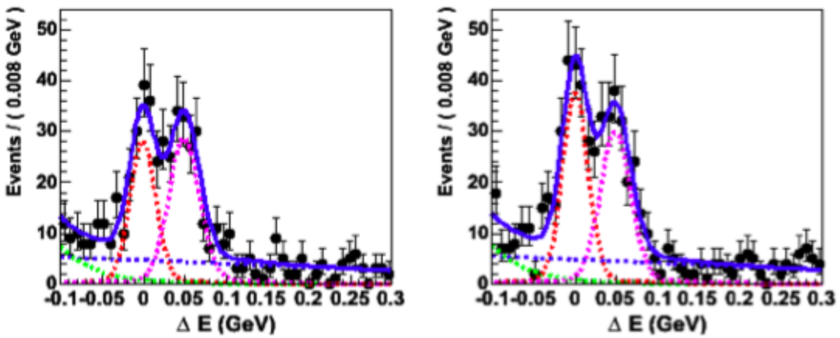
772M BB (final dataset)

CP even:
$D^0 \to K^+K^-, \pi^+\pi^-$



$R_+ = 1.03 \pm 0.07 \pm 0.03$
$A_+ = 0.29 \pm 0.06 \pm 0.02$

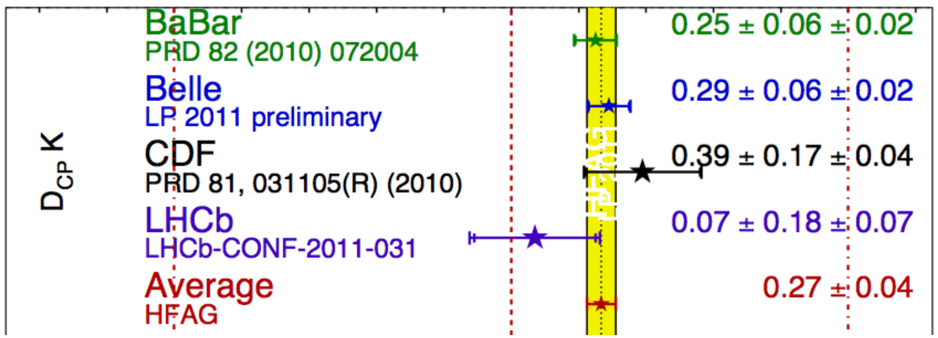
CP odd:
$D^0 \to K_S\pi^0, K_S\eta$



$R_- = 1.13 \pm 0.09 \pm 0.05$
$A_- = -0.12 \pm 0.06 \pm 0.01$

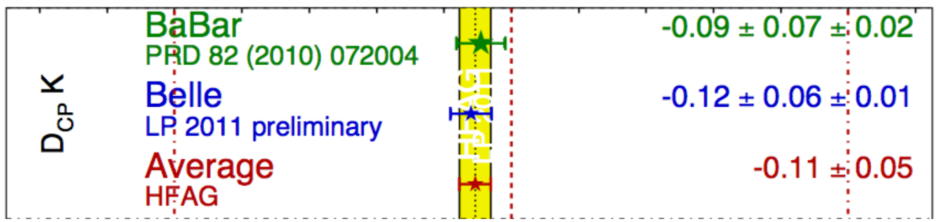
A_{CP+} Averages

HFAG
LP 2011
PRELIMINARY



A_{CP-} Averages

HFAG
LP 2011
PRELIMINARY



Atwood-Dunietz-Soni method

[PRL 78, 3257 (1997); PRD 63, 036005 (2001)]

- The common final state of $D^0/\bar{D}^0$ can be reached either through a Cabibbo-favored ($D^0 \to K^-\pi^+$) or a doubly-Cabibbo-suppressed decay ($D^0 \to K^+\pi^-$)
- Interference between competing amplitudes possibly larger than in GLW

$$R_{ADS} \equiv \frac{B(B^- \to D_{K^+\pi^-} K^-) + B(B^+ \to D_{K^-\pi^+} K^+)}{B(B^- \to D_{K^-\pi^+} K^-) + B(B^+ \to D_{K^+\pi^-} K^+)}$$

$$= r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_b + \delta_c) \cos\varphi_3$$

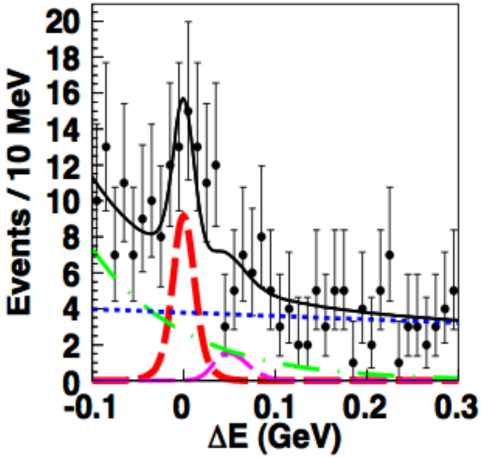
$$A_{ADS} \equiv \frac{B(B^- \to D_{K^+\pi^-} K^-) - B(B^+ \to D_{K^-\pi^+} K^+)}{B(B^- \to D_{K^+\pi^-} K^-) + B(B^+ \to D_{K^-\pi^+} K^+)} = \frac{2 r_B r_D \sin(\delta_b + \delta_c) \sin\varphi_3}{R_{ADS}}$$

- 2 observables
- 5 unknowns (r_B, r_D, δ_b, δ_c, ϕ_3)
- Requires external input

ADS measurement at Belle

772M BB (final dataset)

Horii et al. (Belle), PRL 106, 231803 (2011)

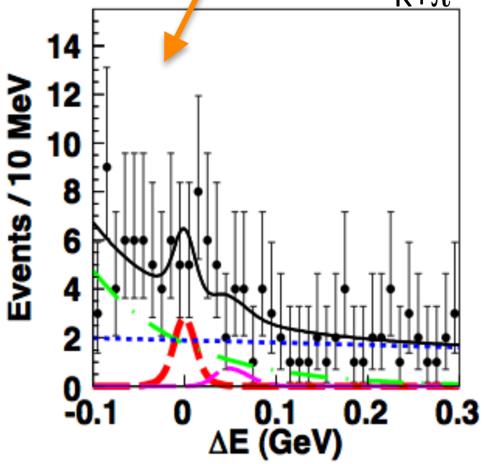


$B^- \to D_{K^+\pi^-} K^-$ + c.c.

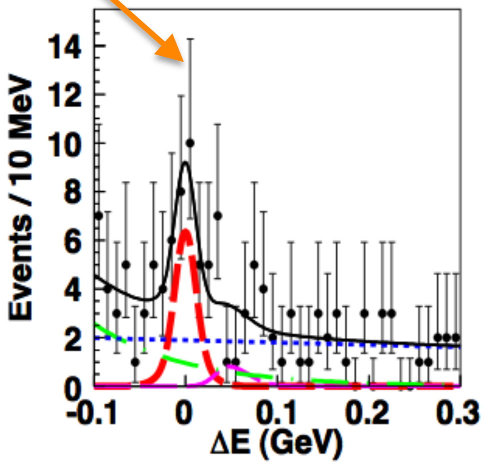
56 +/- 15 events

- Strong continuum suppression using neural network
- First evidence (4.1 sigma) for $B \to D_{K^+\pi^-} K^-$ signal

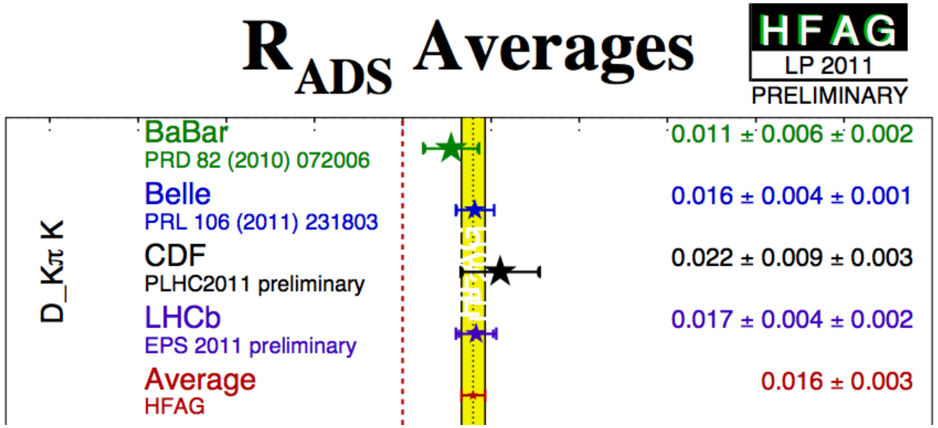
$B^- \to D_{K^+\pi^-} K^-$

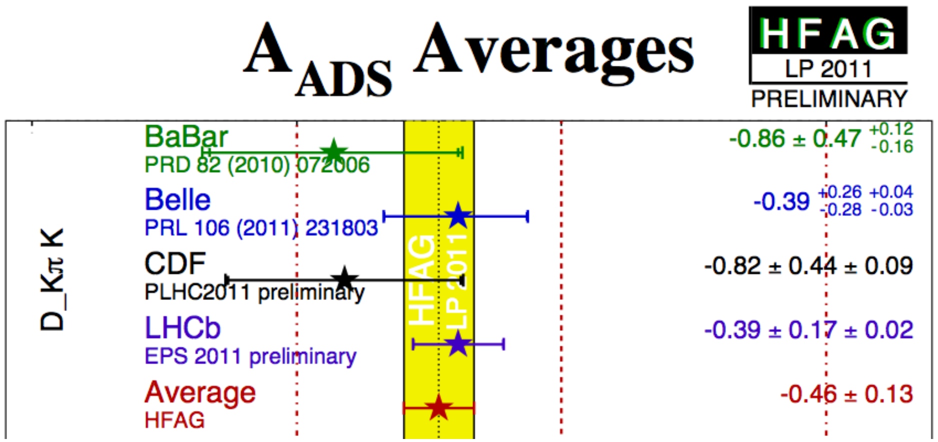


$B^+ \to D_{K^-\pi^+} K^+$



$$\mathcal{R}_{DK} = [1.63^{+0.44}_{-0.41}(\text{stat})^{+0.07}_{-0.13}(\text{syst})] \times 10^{-2}$$
$$\mathcal{A}_{DK} = -0.39^{+0.26}_{-0.28}(\text{stat})^{+0.04}_{-0.03}(\text{syst})$$





- Using $B^- \to D^* K^-$, $D^{*0} \to D^0 \pi^0$ and $D^{*0} \to D^0 \gamma$ adds 4 more observables but only 2 more parameters (r^*, δ^*)
- Taking only r_D and δ_c as external inputs, allows to constrain r_B, δ_b and ϕ_3