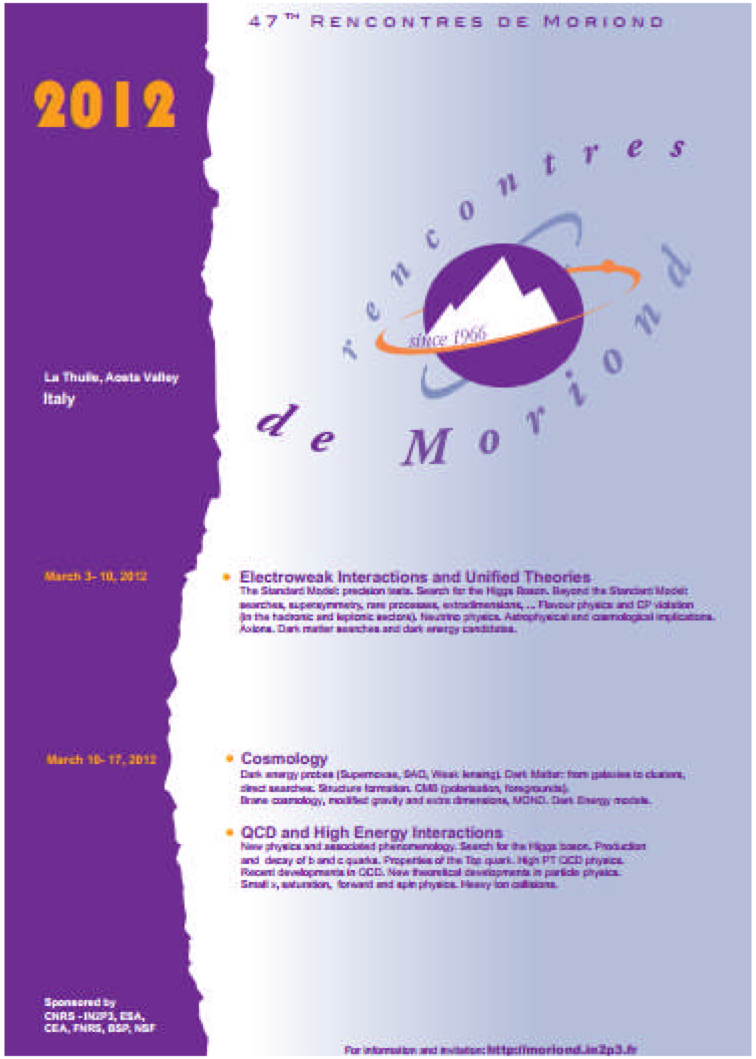
Recent CP violation results from BELLE



Gagan Mohanty
Tata Institute (TIFR), Mumbai

Outline of the talk

1) $\sin(2\varphi_1)$ in $B^0 \rightarrow (c\bar{c})K^0$ decays
2) $\sin(2\varphi_1)$ using B-π tagging at $\Upsilon(5S)$
3) φ_3 in a model-independent DP study
4) φ_3 using GLW and ADS methods
5) Direct CP violation in $B^\pm \rightarrow \eta h^\pm$
6) Conclusions and future prospect

CP violation in the standard model

- Single phase in the CKM matrix (flavor $\rightleftharpoons$ mass eigenstates) is the key piece

$$V = \begin{pmatrix} V_{ud} = 1 - \frac{1}{2}\lambda^2 & V_{us} = \lambda & V_{ub} = A\lambda^3(\rho - i\eta) \\ V_{cd} = -\lambda & V_{cs} = 1 - \frac{1}{2}\lambda^2 & V_{cb} = A\lambda^2 \\ V_{td} = A\lambda^3(1 - \rho - i\eta) & V_{ts} = -A\lambda^2 & V_{tb} = 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Wolfenstein, PRL 51, 1945 (1983)

$\lambda \sim 0.22$	$A \sim 0.80$
$\rho \sim 0.16$	$\eta \sim 0.34$

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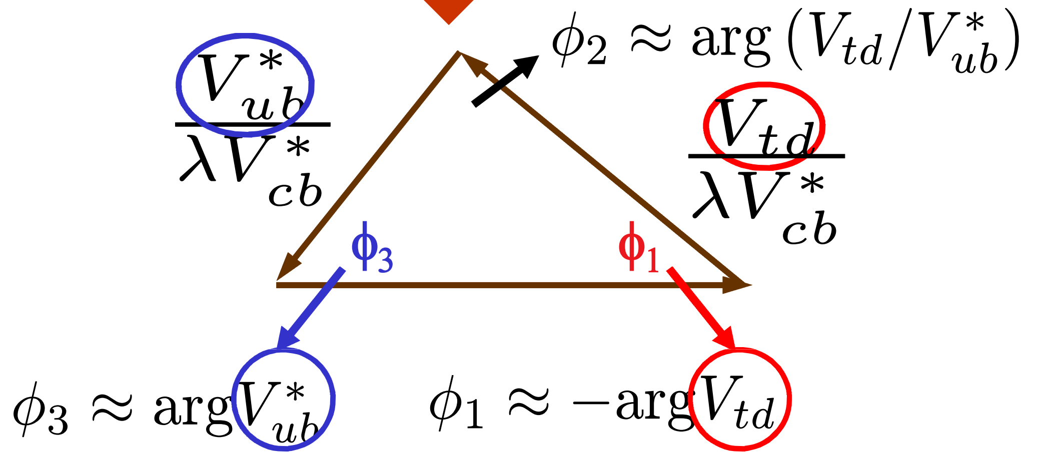
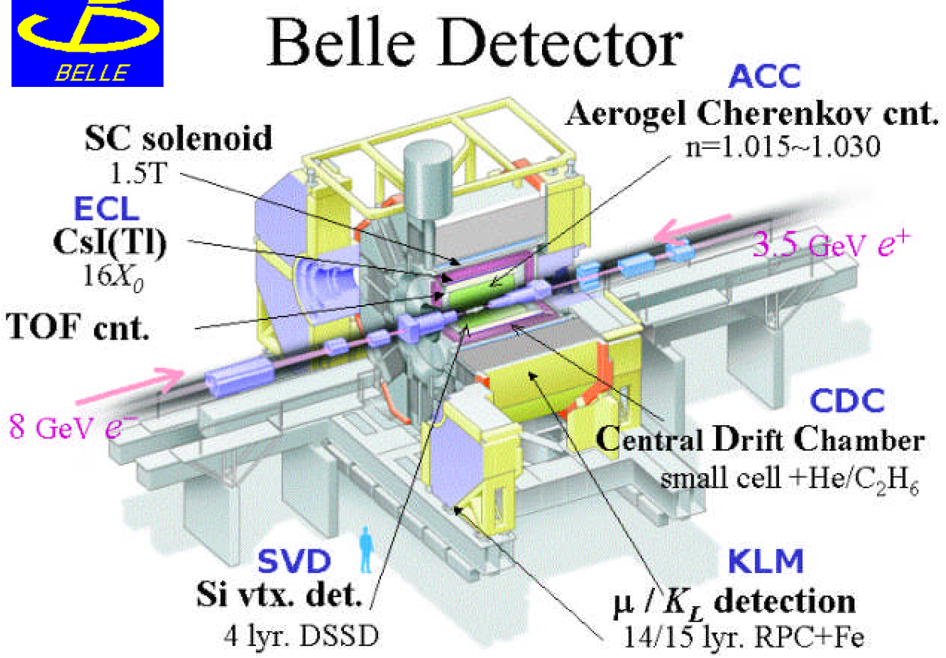


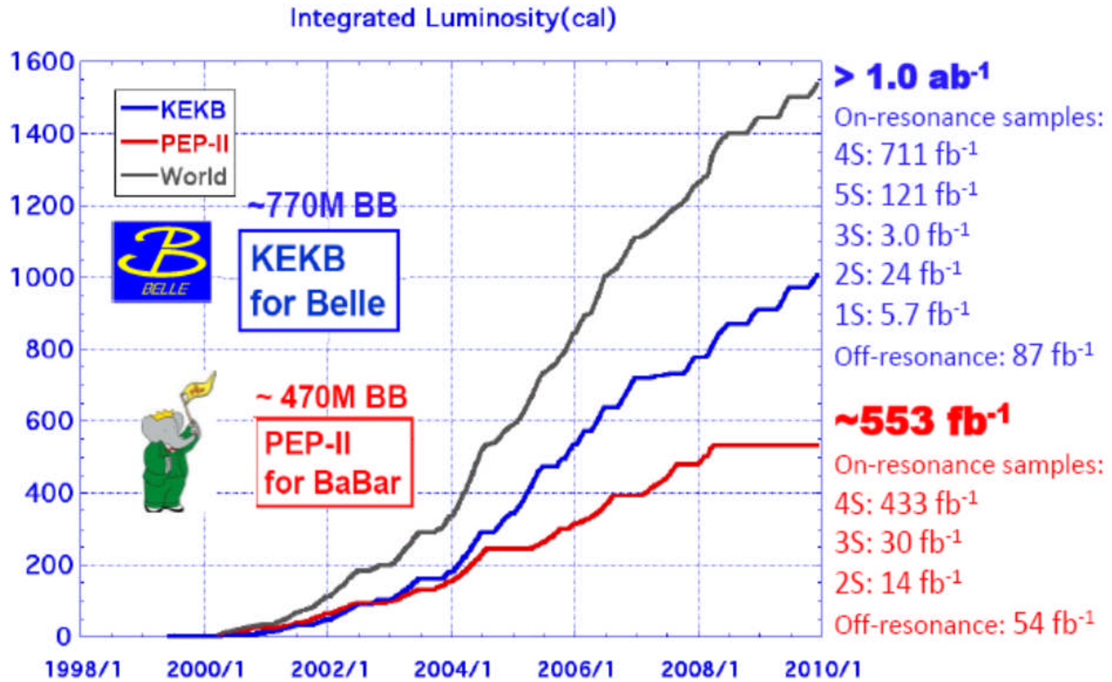
- Check consistency of the CKM framework by precisely measuring the sides and angles of the unitarity triangle
- Possible inconsistency between various measurements could be interpreted as potential new physics contribution

Detector and data



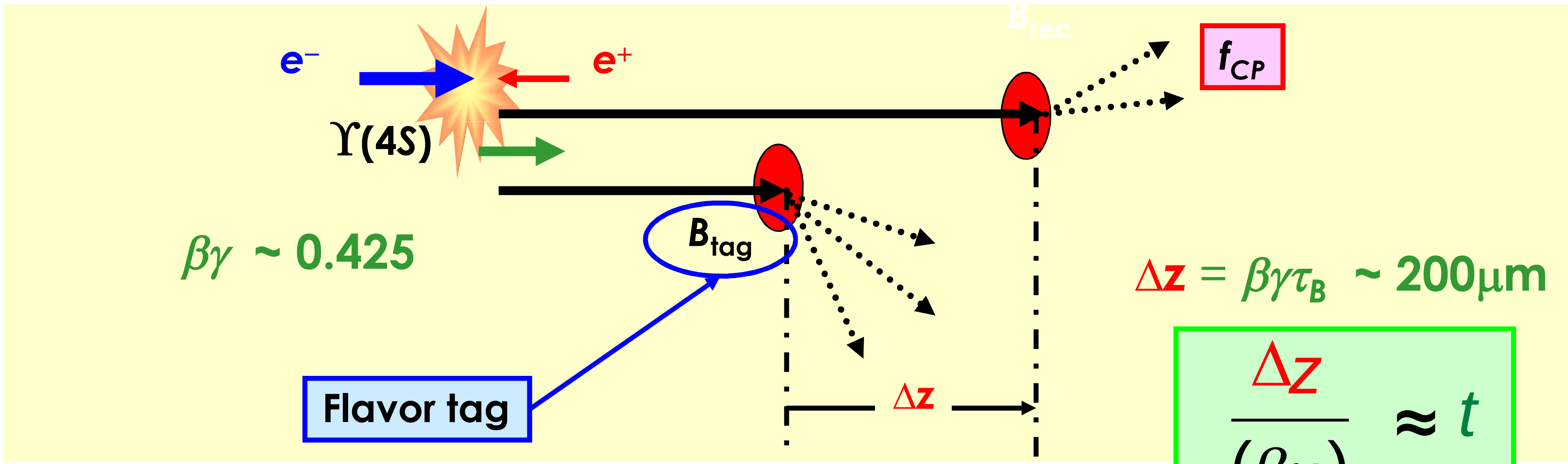
- Large-solid-angle magnetic spectrometer that operated at the KEKB asymmetric-energy e^+e^- collider
- Goal: CP violation in the B system, and rare decays of B, D mesons and τ leptons as an indirect probe of the SM
- Stopped taking data w.e.f. June 2010 to make way for the planned upgrade ➡ Belle II at SuperKEKB

- World's largest samples of Υ(4S), Υ(5S), Υ(1S) and Υ(2S) data in clean e^+e^- environment
- Results presented here comprise the full Υ(4S) [711 fb^{-1} ➡ 772M $B\bar{B}$] and Υ(5S) [121 fb^{-1}] data



How to measure CP violation?

- Reconstruct the $B \rightarrow f_{CP}$ decay
- Measure the proper time difference (t) between the two B mesons



$$\frac{\Delta z}{(\beta\gamma)_{\Upsilon}} \approx t$$

- Determine the flavor of B_{tag} (whether B^0 or $\bar{B}^0$) and then evaluate

$$A_{CP}(t) = \frac{N[\bar{B}^0(t) \rightarrow f_{CP}] - N[B^0(t) \rightarrow f_{CP}]}{N[\bar{B}^0(t) \rightarrow f_{CP}] + N[B^0(t) \rightarrow f_{CP}]} \qquad S_f \sin(\Delta m t) + A_f \cos(\Delta m t)$$

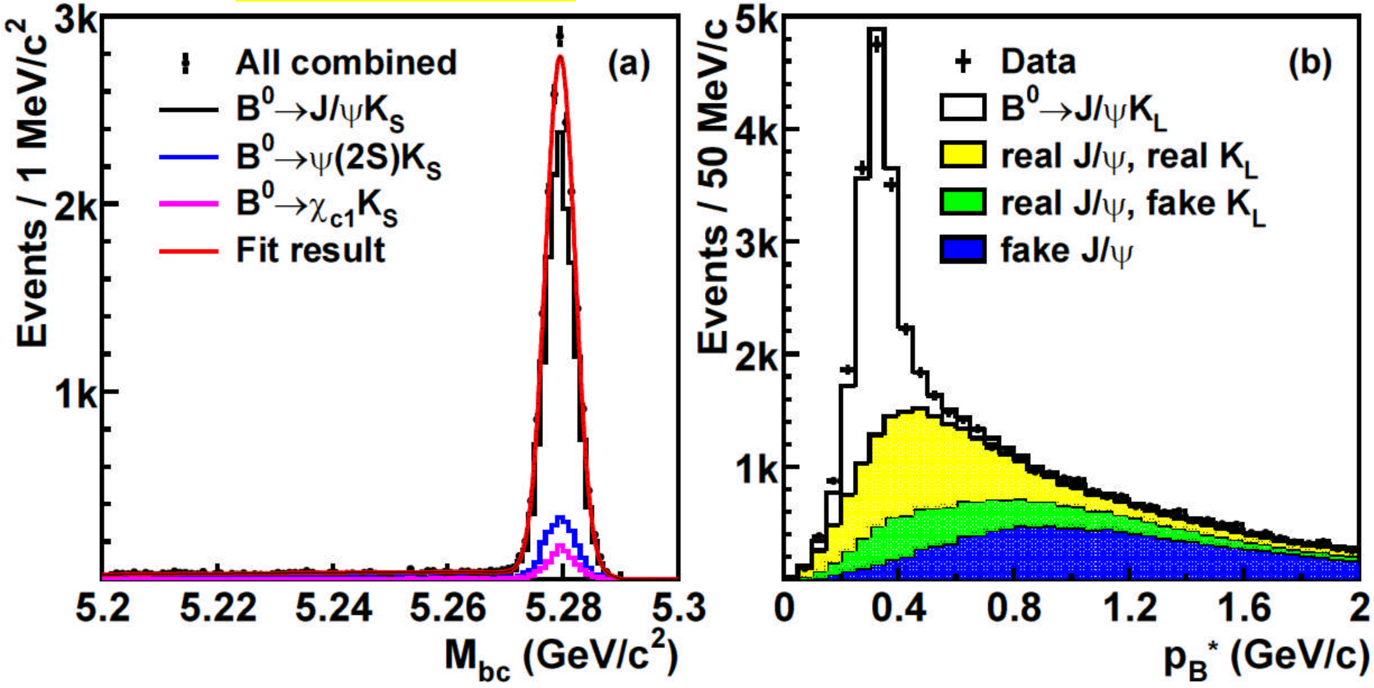
- S_f and A_f are measures of mixing-induced and direct CP violation, respectively

$\sin(2\varphi_1)$ in $B^0 \to (c\bar{c})K^0$ decays

arXiv:1201.4643

Submitted to PRL

- Golden mode for CP violation study with very small theoretical uncertainty and also experimentally easy to identify
- Final measurement with 772M $B\bar{B}$ pairs
- In addition to more data, improved track reconstruction algo. and finely retuned ECL seed threshold (~18% improvement)
- CP-odd eigenstates $J/\psi K_S$, $\psi(2S)K_S$ and $\chi_{c1}K_S$, and CP-even eigenstate $J/\psi K_L$



Decay mode	ξ_f	$N_{\rm sig}$	Purity (%)
$J/\psi K_S^0$	-1	12649 ± 114	97
$\psi(2S)(\ell^+\ell^-)K_S^0$	-1	904 ± 31	92
$\psi(2S)(J/\psi\pi^+\pi^-)K_S^0$	-1	1067 ± 33	90
$\chi_{c1}K_S^0$	-1	940 ± 33	86
$J/\psi K_L^0$	$+1$	10040 ± 154	63

$\sin(2\varphi_1)$ in $B^0 \rightarrow (c\bar{c})K^0$ decays

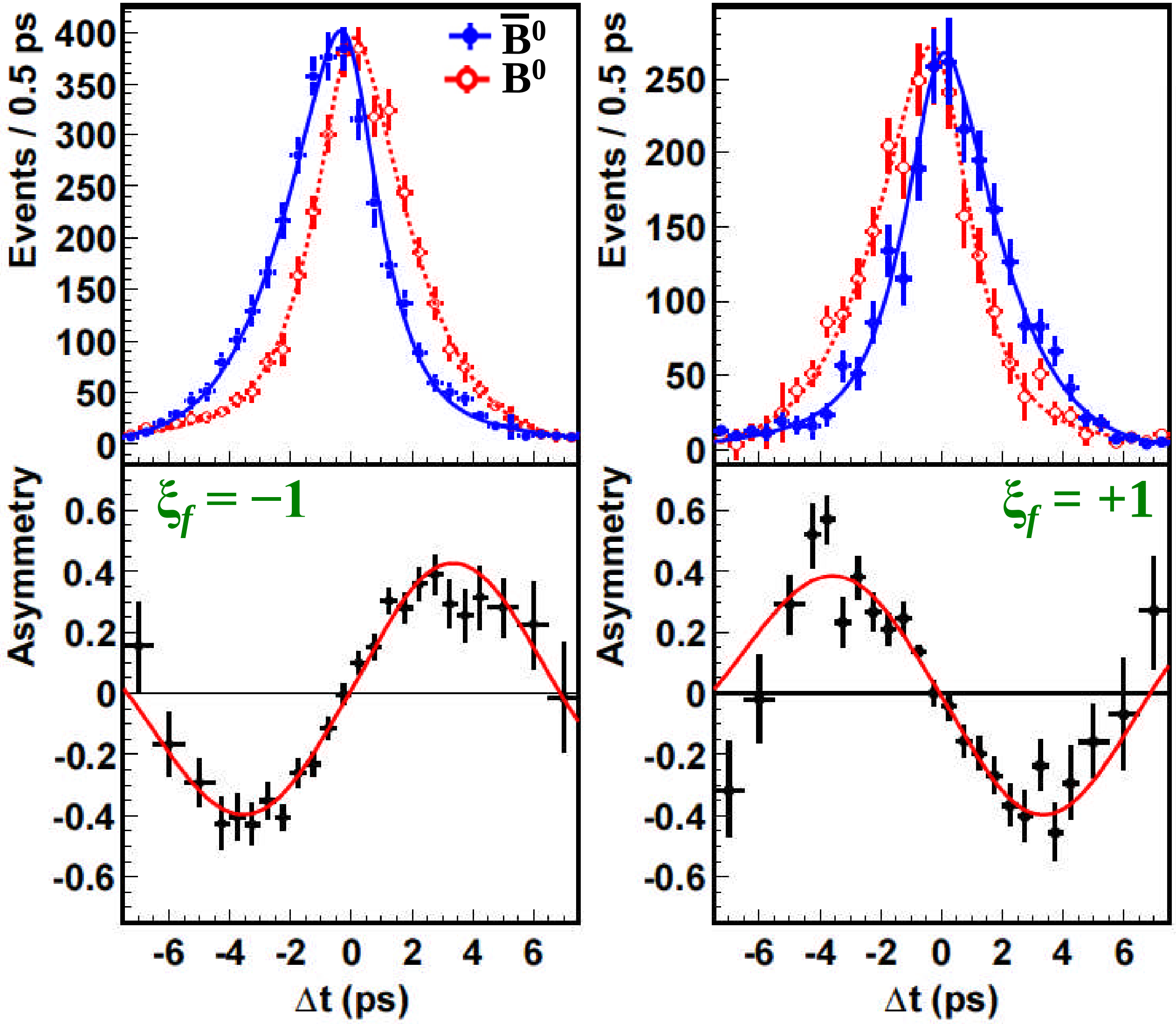
- Most precise measurement of the mixing-induced CP violation in B-meson decay
- Asymmetry pattern in line with the CP eigenvalue of the decay final state
- Direct CP asymmetry is consistent with zero, as expected ➡ negligible height difference between B^0 and $\bar{B}^0$ tagged decays

- Vertex reconstruction is the major source of the systematic uncertainty for $\sin(2\varphi_1)$ followed by Δt resolution function
- In case of A_f the tag-side interference is the main contributor

arXiv:1201.4643

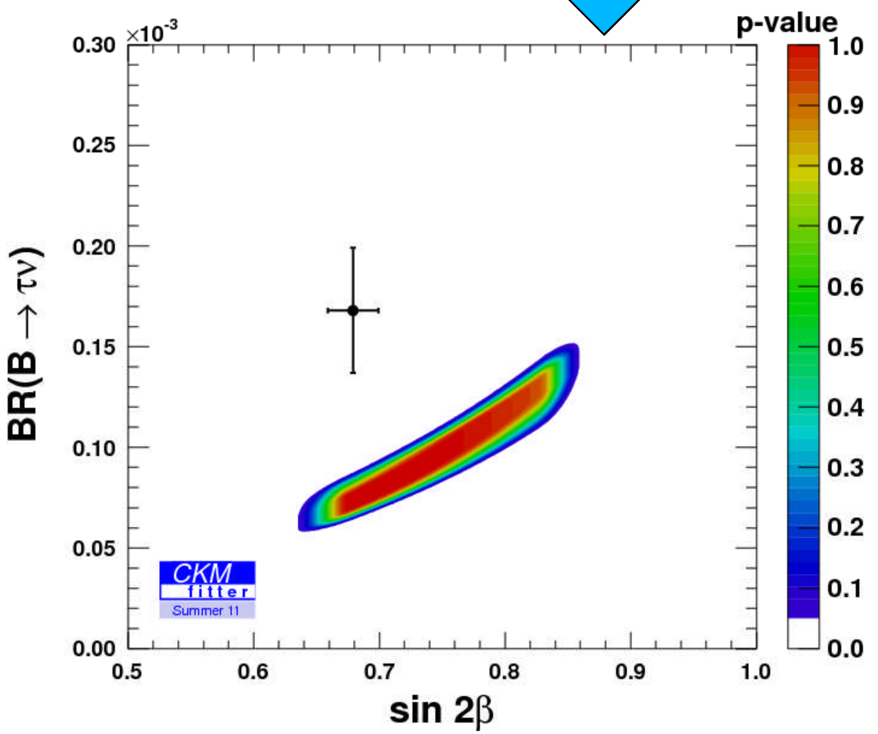
Submitted to PRL

$$\sin 2\phi_1 = 0.667 \pm 0.023(\text{stat}) \pm 0.012(\text{syst})$$
$$\mathcal{A}_f = 0.006 \pm 0.016(\text{stat}) \pm 0.012(\text{syst})$$

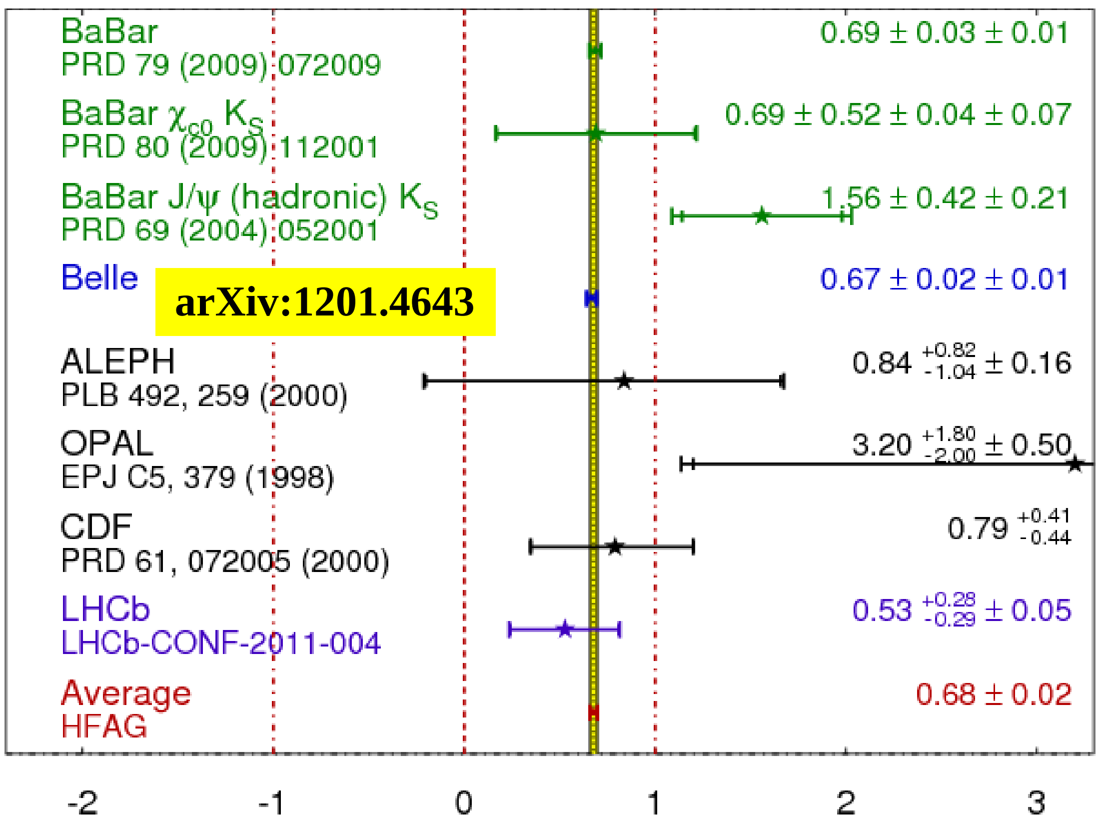


A solid anchor for the SM

- Provides a great SM reference point against which to test for evidence of physics beyond it
- A recent example is close to 2.8σ discrepancy between the measured BF($B^+ \to \tau^+\nu_\tau$) and its indirect determination from a global fit in which $\sin(2\varphi_1)$ plays a major role



$\sin(2\beta) \equiv \sin(2\phi_1)$

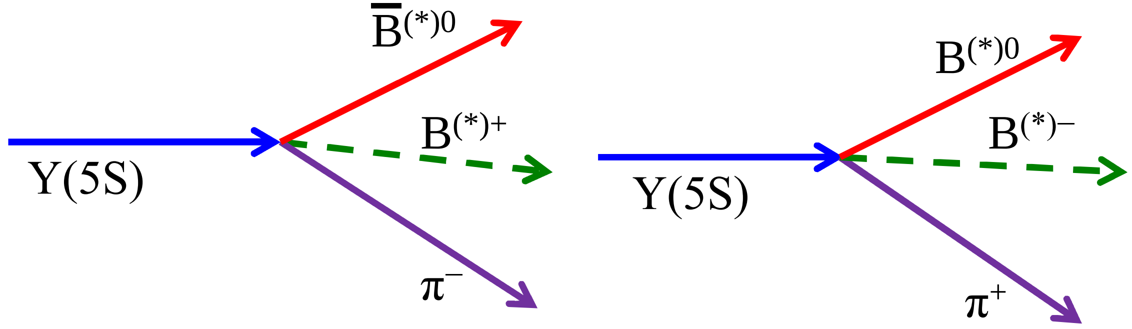


- Important to improve the precision on directly measured BF($B^+ \to \tau^+\nu_\tau$) to confront this tantalizing difference

$\sin(2\varphi_1)$ with a new method using $\Upsilon(5S)$ data

- Charge of the accompanying pion tags flavor of the neutral B meson
- No need to explicitly reconstruct the charged B candidate ➡ use

$$M^2_{\rm miss} \equiv [P_{\rm total} - (P_B + P_{\pi^\pm})]^2$$



B-π tagging

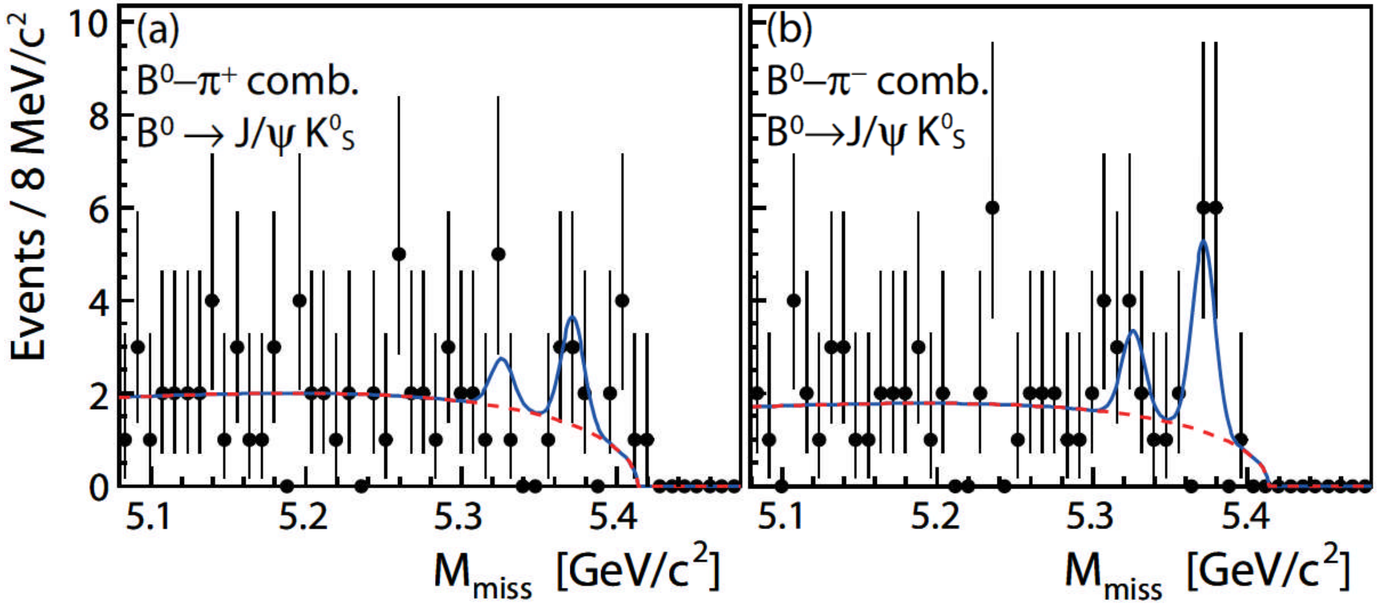
- Extract $\sin(2\varphi_1)$ from $A_{BB\pi} \equiv \frac{N_{BB\pi^-} - N_{BB\pi^+}}{N_{BB\pi^-} + N_{BB\pi^+}} = \frac{Sx+A}{1+x^2}$

S and *A* are mixing-induced and direct CP violation parameters and $x = (m_H - m_L)/\Gamma$, where $m_{H(L)}$ is the mass of the heavy (light) neutral B mass eigenstate and Γ is their average decay width

arXiv:1201.3502

Accepted to PRL

- Plots presented are results of a fit to the missing mass for π^+ & π^--tagged events
- Two peaks denote $B\overline{B}^*\pi + B^*\overline{B}\pi$ (first) and $B^*\overline{B}^*\pi$ (second) contributions



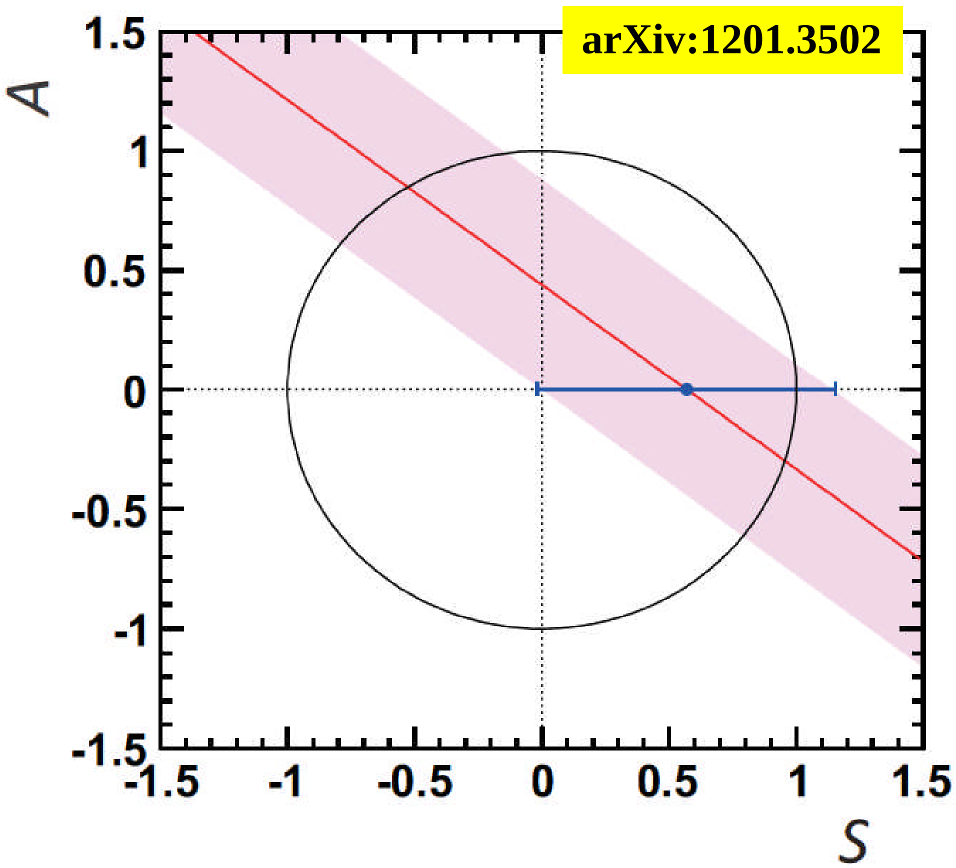
$\sin(2\varphi_1)$ with a new method using Υ(5S) data

- The combined fit yields number of $B\pi^+$ ($B\pi^-$)-tagged events to be 7.8±3.9 (13.7±5.3)

$$A_{BB\pi} = 0.28 \pm 0.28(\mathrm{stat})$$

- Assuming direct CP violation term *A* to be zero and using the world-average value of the mixing parameter *x* (0.771±0.007), we obtain

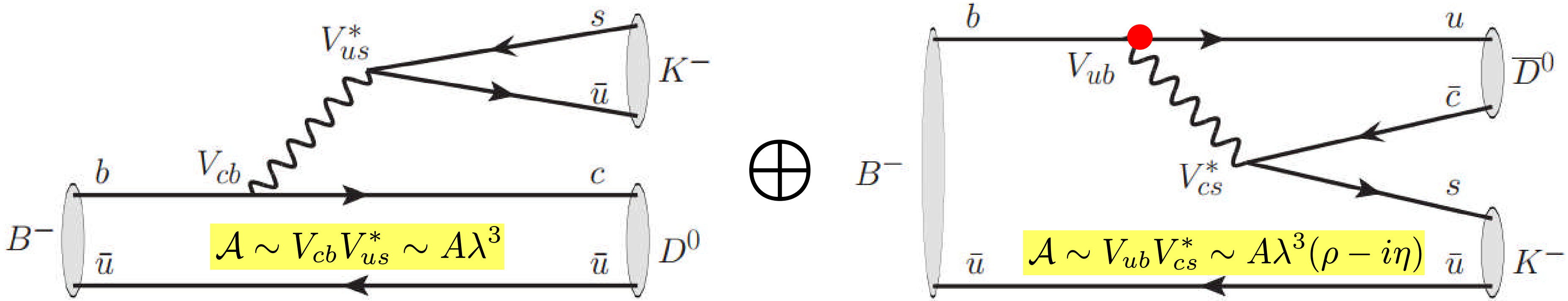
$$\sin 2\phi_1 = 0.57 \pm 0.58(\mathrm{stat}) \pm 0.06(\mathrm{syst})$$



- Dominant systematic uncertainty from the parameters fixed to MC values

- This method is complimentary to time-dependent analyses carried at the Υ(4S) peak using flavor tagging
- At the moment we are limited by the available statistics
- Has a great potential for experiments at the super flavor factory

Measurement of the angle φ_3



- Interference between the two amplitudes where both D^0 and $\bar{D}^0$ coming from B^+ or B^- decay to a common final state
- Current sensitivity is dominated by measurements in the D mesons decay to three-body final states, e.g. $K_S\pi^+\pi^-$, that exploit difference between the decay Dalitz plot (DP)

Giri et al., PRD 68, 054018 (2003)

Our results with conventional Dalitz method

PRD 81, 112002 (2010)

$$\phi_3 = (78.4^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^\circ$$

$$r_B = 0.160^{+0.040}_{-0.038} \pm 0.011^{+0.050}_{-0.010}$$

➡ Uncertainties are respectively statistical, systematic and DP model dependence

- Accuracy in the DP model description (last error in above results) is the second largest contributor to φ_3 following the statistical uncertainty
- It would *call the shot* in the precise determination of φ_3 at the next-generation flavor factories ➡ look for a suitable alternative

Model-independent DP analysis

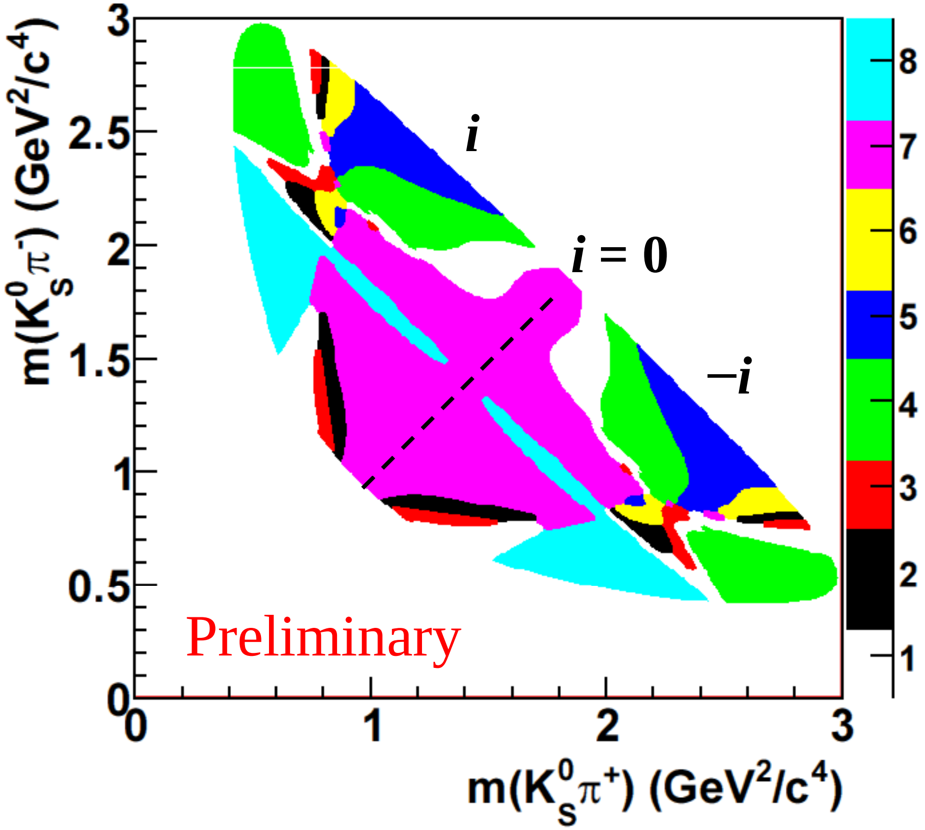
- DP density of the D decay from $B^\pm \to DK^\pm$

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

- $\bar{D}^0 \to K_S\pi^+\pi^-$ amplitude f_D is parameterized as a set of quasi-two-body amplitudes in the conventional DP method

Giri et al., PRD 68, 054018 (2003)

Bonder, Poluektov, EPJ C 55, 51 (2008)



- In contrast, model-independent approach invokes study of the binned DP

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

where $x_\pm = r_B \cos(\delta_B \pm \phi_3)$, $y_\pm = r_B \sin(\delta_B \pm \phi_3)$

M_i: # events in $D \to K_S\pi^+\pi^-$ bins from $B^\pm \to DK^\pm$

K_i: # events in bins of flavor $\bar{D}^0 \to K_S\pi^+\pi^-$ from $D^* \to D\pi$

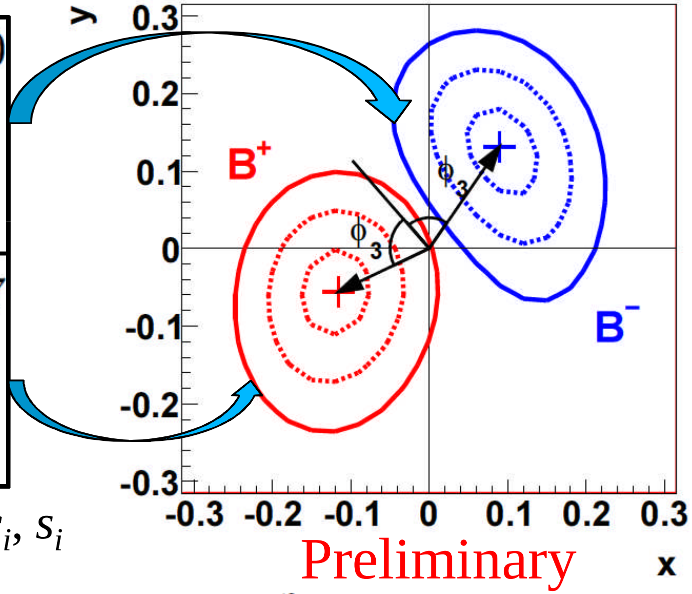
c_i, s_i contain info about the strong-phase difference between symmetric DP points $[m^2(K_S\pi^+), m^2(K_S\pi^-)]$ and $[m^2(K_S\pi^-), m^2(K_S\pi^+)]$

- $c_i = \langle\cos\Delta\delta_D\rangle$ and $s_i = \langle\sin\Delta\delta_D\rangle$ are the external inputs, obtained from quantum correlated $D^0\bar{D}^0$ decays at the $\psi(3770)$ resonance in CLEO-c **PRD 82, 112006 (2010)**

φ_3 from model independent DP fit

- Combined likelihood fit to signal selection variables in all bins with floating parameters: $x_\pm$, $y_\pm$, overall normalization and background fractions

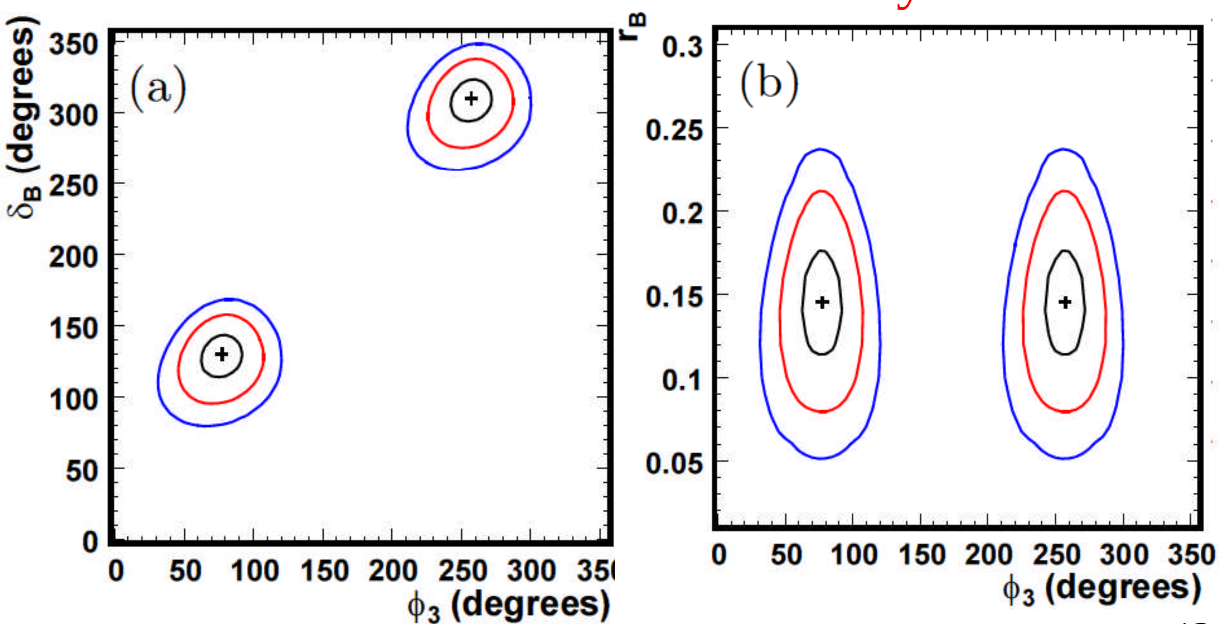
x_-	$+0.095 \pm 0.045 \pm 0.014 \pm 0.010$
y_-	$+0.137^{+0.053}_{-0.057} \pm 0.015 \pm 0.023$
$\mathrm{corr}(x_-, y_-)$	-0.315
x_+	$-0.110 \pm 0.043 \pm 0.014 \pm 0.007$
y_+	$-0.050^{+0.052}_{-0.055} \pm 0.011 \pm 0.017$
$\mathrm{corr}(x_+, y_+)$	$+0.059$



Uncertainties are statistical, systematic and precision on c_i, s_i

$$\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$$
$$\delta_B = (129.9 \pm 15.0 \pm 3.8 \pm 4.7)^\circ$$
$$r_B = 0.145 \pm 0.030 \pm 0.010 \pm 0.011$$

- 2.7σ evidence for direct CP violation (φ_3 being nonzero)
- 8.9° model error ➡ 4.3° ☺ stat. error little worse due to (a) the method itself, (b) r_B is getting smaller ➡ $\sigma \sim 1/r_B$

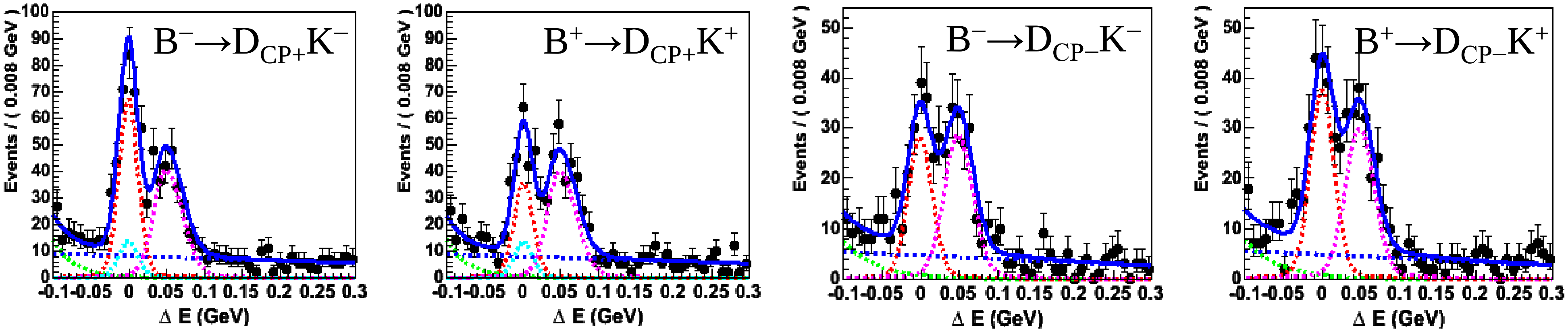


φ_3 using GLW and ADS methods

- Two complementary approaches where D mesons decay to
  1) CP states, e.g., K^+K^-, $\pi^+\pi^-$ (CP+) & $K_S\pi^0$, $K_S\eta$ (CP−) GLW
  2) doubly CKM suppressed final state ADS

PLB 253, 483 (1991)
PLB 265, 172 (1991)

PRL 78, 3257 (1997) PRD 63, 036005 (1991)

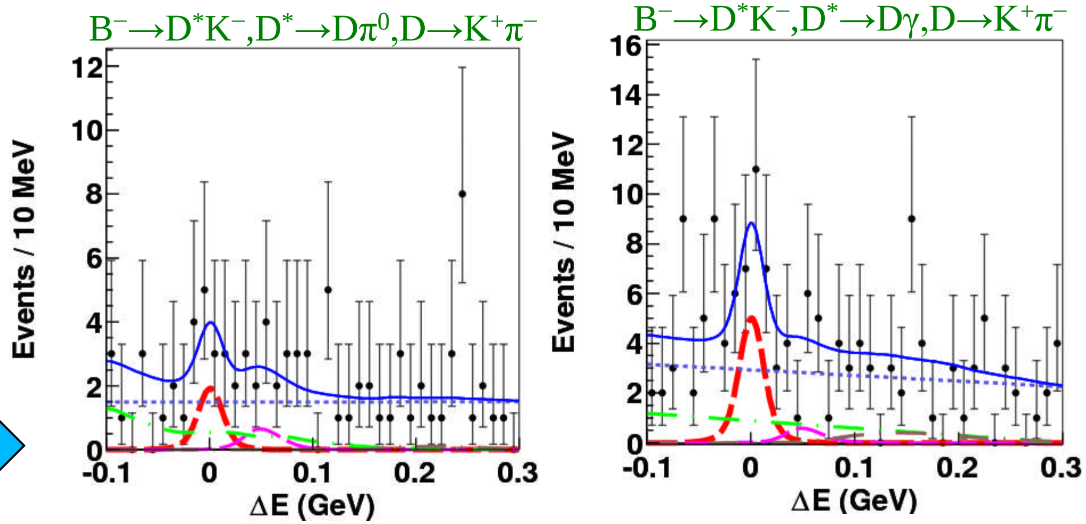


- Observables sensitive to φ_3:

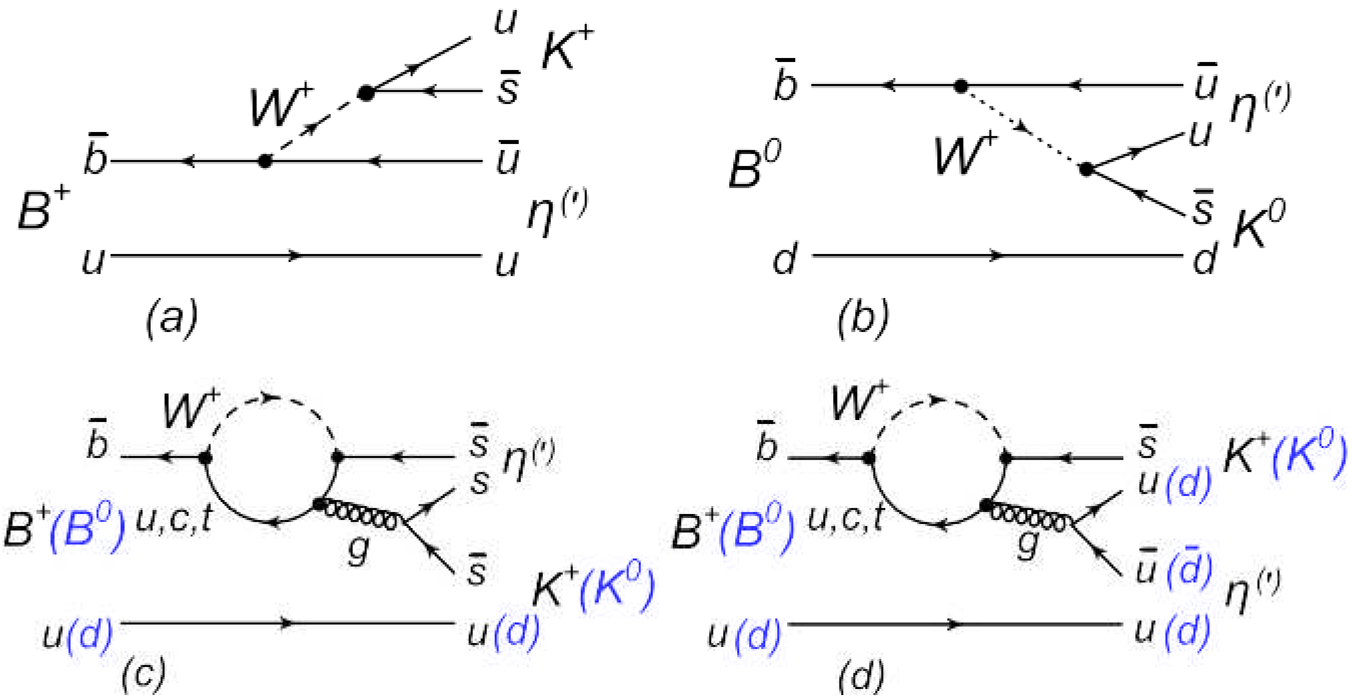
$$R_{CP+} = 1.03 \pm 0.07 \pm 0.03$$
$$R_{CP-} = 1.13 \pm 0.09 \pm 0.05$$
$$A_{CP+} = 0.29 \pm 0.06 \pm 0.02$$
CPV
$$A_{CP-} = -0.12 \pm 0.06 \pm 0.01$$

- 1st Evidence for ADS mode $B \to D^*K$ (3.5σ significance)

Preliminary



Study of B → $\eta^{(')}h$ ($h = K,\pi$)



- Large B →η'K and small B → ηK branching fractions are an artifact of η-η' mixing along with constructive and destructive interference between the two penguin processes, (c) and (d)

Lipkin, PLB 254, 247 (1991)

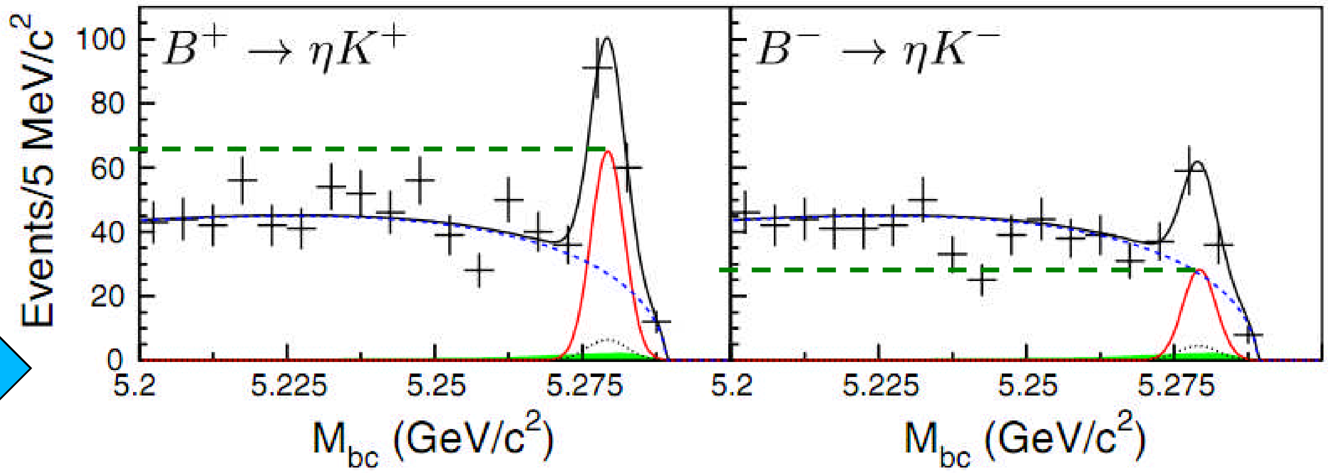
- Direct CPV effect could be significant depending on the level of interference between b → d penguin and b → u tree diagrams

- Owing to the color-suppressed tree amplitude in case of B → ηK^0 (b), its branching fraction is expected to be lower than that of $B^\pm \to \eta K^\pm$

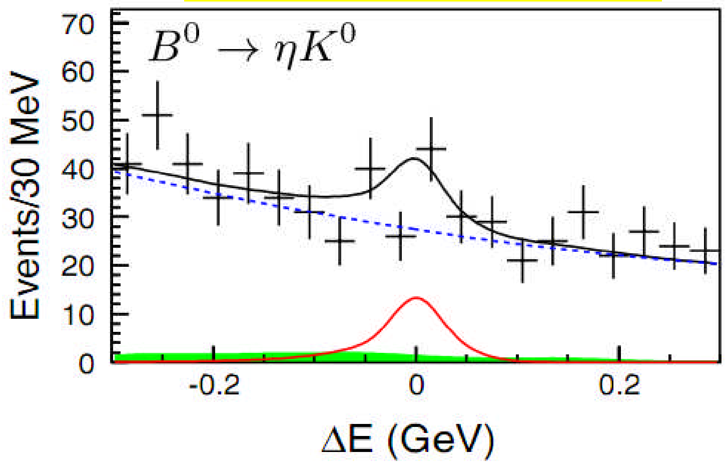
Evidence for direct CPV in B→ηh and observation of $B^0 \to \eta K^0$

	$\Sigma(\mathcal{Y})$	$\mathcal{B}\ (10^{-6})$	A_{CP}	$\Sigma(A_{CP})$
$B^\pm \to \eta K^\pm$	13.2	$2.12 \pm 0.23 \pm 0.11$	$-0.38 \pm 0.11 \pm 0.01$	3.8
$B^\pm \to \eta \pi^\pm$	22.4	$4.07 \pm 0.26 \pm 0.21$	$-0.19 \pm 0.06 \pm 0.01$	3.0

- Dominant systematics errors on BF are due to MC modeling of η and π^0 (4% each)
- Clear evidence for direct CP violation



PRL 108, 031801 (2012)



- First observation of the decay $B^0 \to \eta K^0$ with a significance of 5.4 standard deviations

$$\mathcal{B}(B^0 \to \eta K^0) = (1.27^{+0.33}_{-0.29} \pm 0.08) \times 10^{-6}$$

Conclusions and future prospect

Results presented here

- Most precise measurement of $\sin(2\varphi_1)$ with $B \to (c\bar{c})K^0$ decays
- Significantly improved results in the $B^0 \to D^{(*)+}D^{(*)-}$ decays ➡ silver mode for $\sin(2\varphi_1)$ See the YSF presentation by B. Kronenbitter
- A new method of B-π tagging to measure $\sin(2\varphi_1)$ at the $\Upsilon(5S)$ resonance
- Model independent DP analysis reducing model uncertainty on φ_3 to 4^o
- Updates of GLW and ADS modes to obtain complimentary constraint on φ_3
- Evidence for direct CP violation in $B^\pm \to \eta h^\pm$

What is in store?

- Many related analyses are ongoing, such as the angle φ_2 of the unitarity triangle and branching fraction measurement of $B^+ \to \tau^+\nu_\tau$
- Looking forward to an exciting summer at Melbourne ☺

Thanks for your kind attention

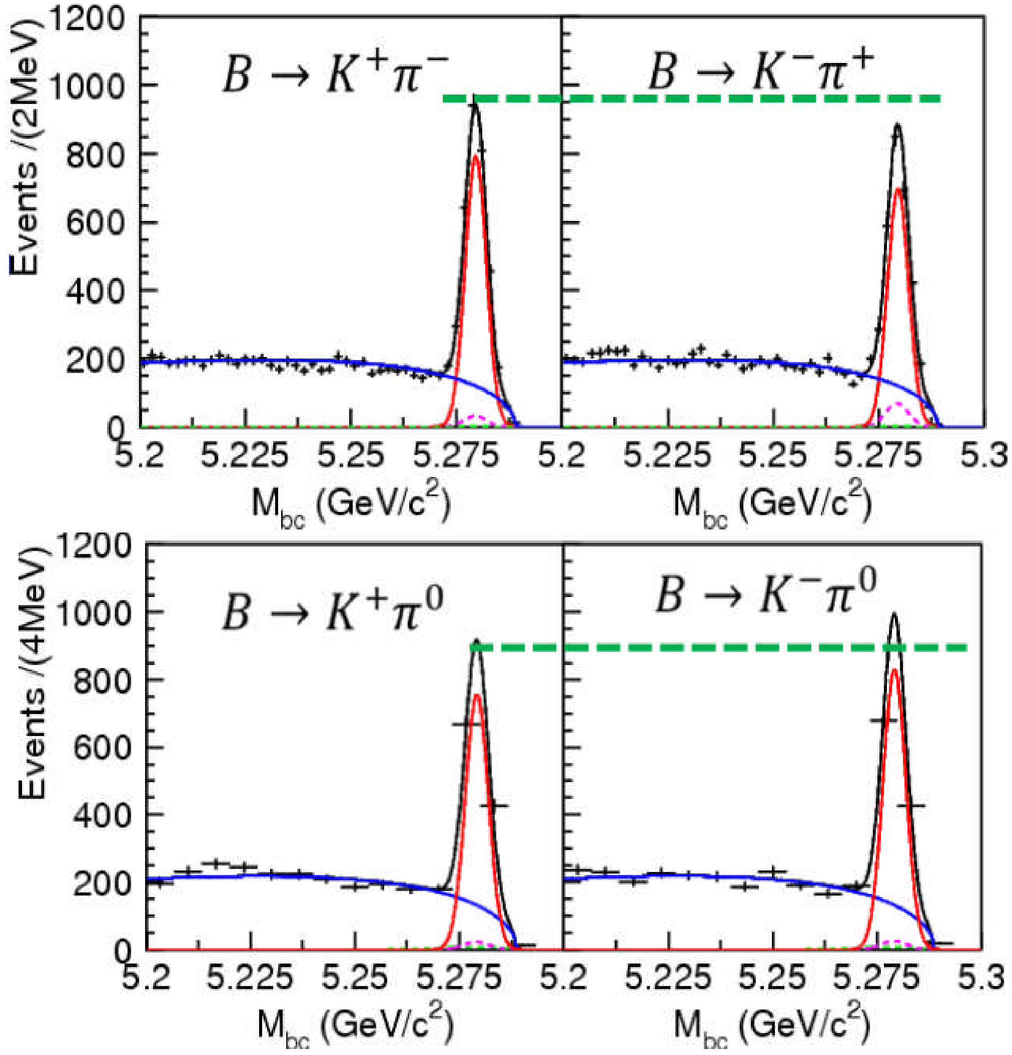
Bonus slides

Summary of systematics in $B \to (c\bar{c})K^0$

	$\sin 2\phi_1$	$\mathcal{A}_f$
Vertex reconstruction	± 0.007	± 0.007
Flavor tagging	± 0.004	± 0.003
Δt resolution function	± 0.007	± 0.001
Physics parameters	± 0.001	< 0.001
Possible fit bias	± 0.004	± 0.005
$J/\psi K_S^0$ signal fraction	± 0.002	± 0.001
$J/\psi K_L^0$ signal fraction	± 0.004	± 0.002
$\psi(2S)K_S^0$ signal fraction	< 0.001	< 0.001
$\chi_{c1}K_S^0$ signal fraction	< 0.001	< 0.001
Background Δt PDFs	± 0.001	< 0.001
Tag-side interference	± 0.001	± 0.008
Total	± 0.012	± 0.012

Study of B → hh' [h(') = K,π]

- A rich ground to probe direct CP violation (mostly two contributing amplitudes, $b \to u$ tree and $b \to s/d$ penguin) and to test various models for B decays
- Potential new physics contribution in electroweak penguins: $\Delta A_{K\pi} = A_{CP}(K\pi^0) - A_{CP}(K\pi)$ and ratios of branching fractions (R_c, R_n)



Nature paper: **Nature 452, 332 (2008)**

$\Delta A_{K\pi} = +0.164 \pm 0.037$ with 4.4σ

Preliminary:

$\Delta A_{K\pi} = +0.112 \pm 0.028$ with 4.0σ

Modes	Belle 2007	Belle 2011
$2\Gamma(K^+\pi^0)/\Gamma(K^0\pi^+)$	$1.08 \pm 0.06 \pm 0.08$	$1.05 \pm 0.03 \pm 0.05$
$\Gamma(K^+\pi^-)/2\Gamma(K^0\pi^0)$	$1.08 \pm 0.08 \pm 0.08$	$1.04 \pm 0.05 \pm 0.06$
$\Gamma(K^+\pi^-)/\Gamma(K^0\pi^+)$	$0.94 \pm 0.04 \pm 0.05$	$0.90 \pm 0.03 \pm 0.03$
$\Gamma(\pi^+\pi^-)/\Gamma(K^+\pi^-)$	$0.26 \pm 0.01 \pm 0.01$	$0.25 \pm 0.01 \pm 0.01$
$\Gamma(\pi^+\pi^-)/2\Gamma(\pi^+\pi^0)$	$0.42 \pm 0.03 \pm 0.02$	$0.46 \pm 0.03 \pm 0.03$
$\Gamma(\pi^+\pi^0)/\Gamma(K^0\pi^0)$	$0.66 \pm 0.07 \pm 0.04$	$0.56 \pm 0.04 \pm 0.03$
$2\Gamma(\pi^+\pi^0)/\Gamma(K^0\pi^+)$	$0.57 \pm 0.04 \pm 0.04$	$0.49 \pm 0.02 \pm 0.03$

- These ratios of BF including R_c and R_n (first two rows) are consistent with SM predictions with different approaches

PRD 72, 114005 (2005) **PRD 68, 054023 (2003)**

PLB 572, 43 (2003) **EPJ C45, 701 (2006)**