RECENT RESULTS ON HADRONIC B DECAYS FROM BELLE

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on behalf of the Belle Collaboration

Rencontres du Vietnam, Windows on the Universe

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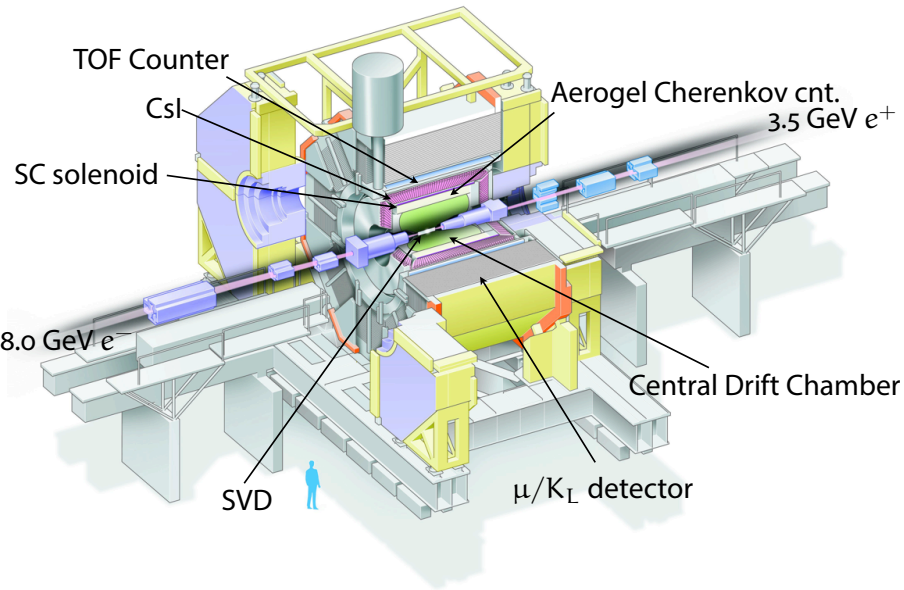
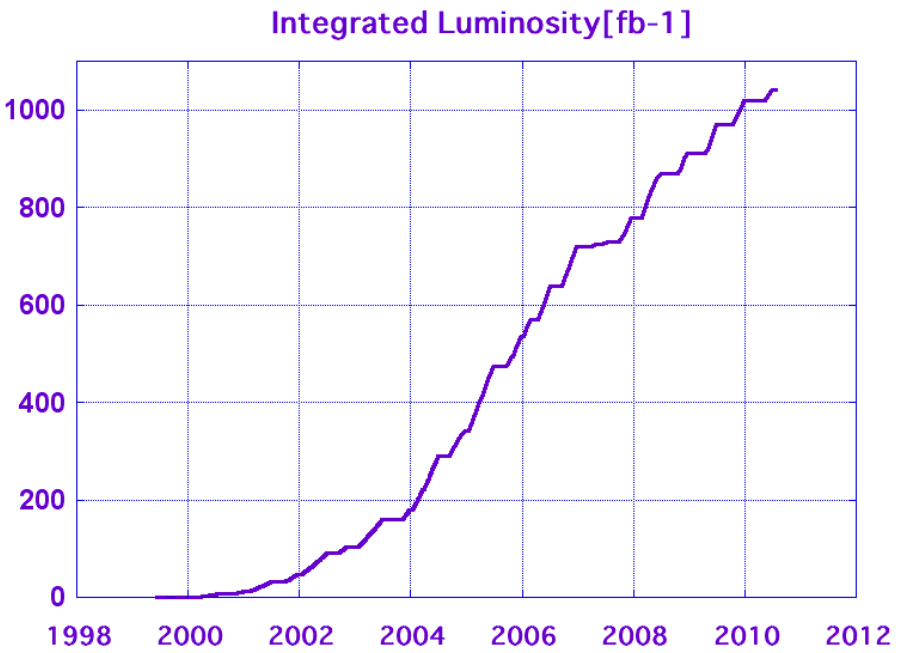
Outline

- Angular analysis of $B^0 \to \phi K^*$ decays and search for CP violation
  - submitted to PRD arXiv:1308.1830 [hep-ex]
- Evidence for the decay $B^0 \to K^+K^-\pi^0$
  - V. Gaur, *et al.* (Belle Collaboration), PRD **87**, 091101(R) (2013)
- Measurement of ϕ_2 in
  - $B \to \pi^+\pi^-$ submitted to PRD arXiv:1302.0551 [hep-ex]
  - $B \to \rho^0\rho^0$ arXiv:1212.4015 [hep-ex]

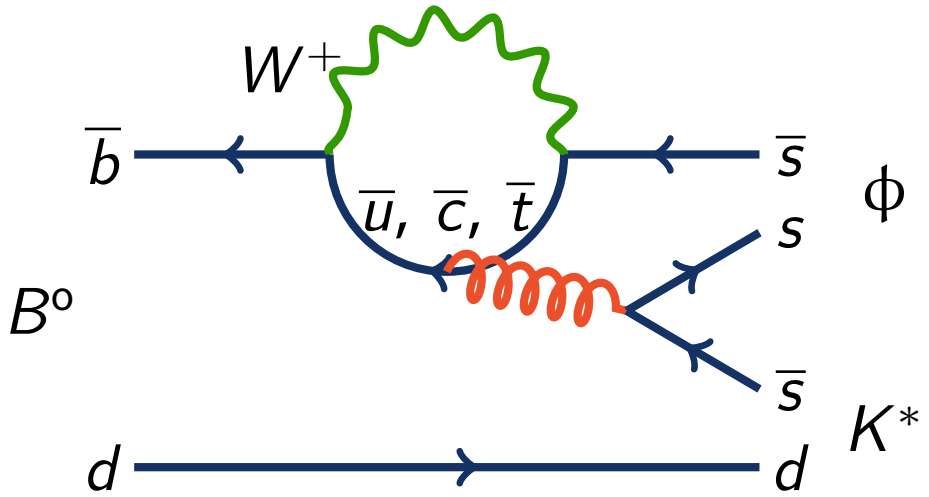
Belle Experiment





- Operated at KEKB accelerator in Tsukuba, Japan (1999–2010)
- KEKB took data mostly on $\Upsilon(4S)$
- 8 GeV $e^- \rightarrow\leftarrow e^+$ 3.5 GeV
- $\Upsilon(4S)$ decays almost entirely to $B\overline{B}$
- $(772 \pm 11) \times 10^6$ $B\overline{B}$ pairs recorded
- Very clean environment for physics studies
- All analyses presented in this talk are based on the full Belle data sample

$B^0 \to \phi K^*$ – motivation



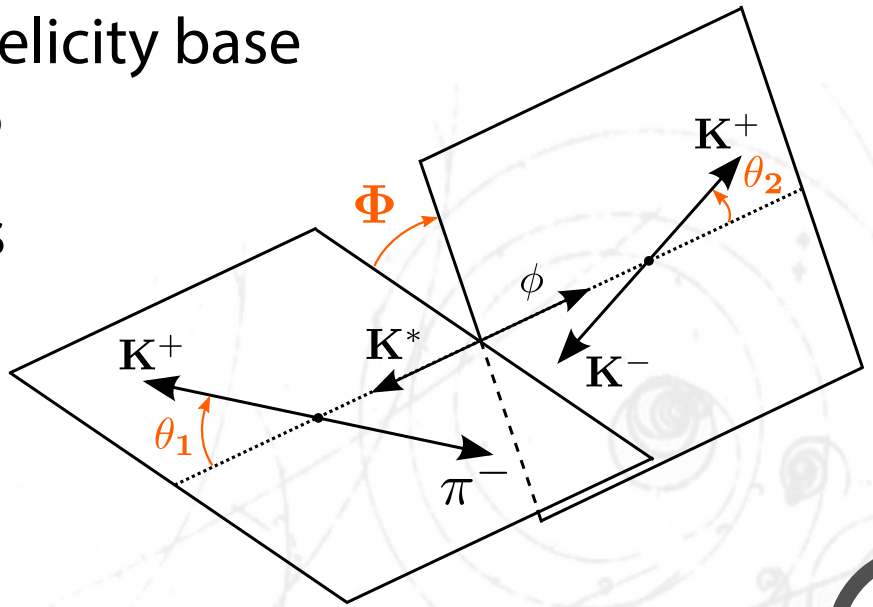
- Proceeds via the $b \to s$ penguin transition in the SM
- Sensitive to possible new particle contributions in the loop
- A baffling pattern in the longitudinal polarisations:

$B^0 \to \phi K^*(892)^0$	$f_L = 0.45 \pm 0.05 \pm 0.02$	Belle PRL **94**, 221804 (2005)
	$f_L = 0.494 \pm 0.034 \pm 0.013$	*BABAR* PRD **78**, 092008 (2008)
$B^0 \to \phi K_2^*(1430)^0$	$f_L = 0.901^{+0.046}_{-0.058} \pm 0.037$	*BABAR* PRD **78**, 092008 (2008)

- QCD factorisation $\to$ expected $f_L \sim 1$
- Negligible direct CP violation expected in the SM

$B^0 \to \phi K^*$ – analysis approach

- Partial wave analysis of $B^0 \to \phi K^*$ with $K^* \to K^+\pi^-$ being
  - scalar $(K\pi)_0^*$ S–wave, $J = 0$
  - vector $K^*(892)^0$ P–wave, $J = 1$
  - tensor $K_2^*(1430)^0$ D–wave, $J = 2$
- Analysis restricted to $K^+\pi^-$ invariant mass < 1.55 GeV/c^2
  - LASS model for S–wave component (includes $K_0^*(1430)^0$)
  - relativistic spin-dependent Breit-Wigner for P– and D–wave
- Angular distributions in the helicity base
- Simultaneous fit to B^0 and $\overline{B}^0$
- in total 26 physics parameters measured in the $B^0 \to \phi K^*$ system



$B^0 \to \phi K^*$ – physics parameters

Parameter	Definition	$\phi(K\pi)^*_0$ $J=0$	$\phi K^*(892)^0$ $J=1$	$\phi K_2^*(1430)^0$ $J=2$
$\mathcal{B}_J$	$\frac{1}{2}(\overline{\Gamma}_J + \Gamma_J)/\Gamma_{\text{total}}$	$\mathcal{B}_0$	$\mathcal{B}_1$	$\mathcal{B}_2$
f_{LJ}	$\frac{1}{2}(\lvert\overline{A}_{J0}\rvert^2/\sum\lvert\overline{A}_{J\lambda}\rvert^2 + \lvert A_{J0}\rvert^2/\sum\lvert A_{J\lambda}\rvert^2)$	–	f_{L1}	f_{L2}
$f_{\perp J}$	$\frac{1}{2}(\lvert\overline{A}_{J\perp}\rvert^2/\sum\lvert\overline{A}_{J\lambda}\rvert^2 + \lvert A_{J\perp}\rvert^2/\sum\lvert A_{J\lambda}\rvert^2)$	–	$f_{\perp 1}$	$f_{\perp 2}$
$\phi_{\parallel J}$	$\frac{1}{2}(\arg(\overline{A}_{J\parallel}/\overline{A}_{J0}) + \arg(A_{J\parallel}/A_{J0}))$	–	$\phi_{\parallel 1}$	$\phi_{\parallel 2}$
$\phi_{\perp J}$	$\frac{1}{2}(\arg(\overline{A}_{J\perp}/\overline{A}_{J0}) + \arg(A_{J\perp}/A_{J0}) - \pi)$	–	$\phi_{\perp 1}$	$\phi_{\perp 2}$
δ_{0J}	$\frac{1}{2}(\arg(\overline{A}_{00}/\overline{A}_{J0}) + \arg(A_{00}/A_{J0}))$	–	δ_{01}	δ_{02}
$\mathcal{A}_{CPJ}$	$(\overline{\Gamma}_J - \Gamma_J)/(\overline{\Gamma}_J + \Gamma_J)$	$\mathcal{A}_{CP0}$	$\mathcal{A}_{CP1}$	$\mathcal{A}_{CP2}$
$\mathcal{A}^0_{CPJ}$	$\frac{\lvert\overline{A}_{J0}\rvert^2/\sum\lvert\overline{A}_{J\lambda}\rvert^2 - \lvert A_{J0}\rvert^2/\sum\lvert A_{J\lambda}\rvert^2}{\lvert\overline{A}_{J0}\rvert^2/\sum\lvert\overline{A}_{J\lambda}\rvert^2 + \lvert A_{J0}\rvert^2/\sum\lvert A_{J\lambda}\rvert^2}$	–	$\mathcal{A}^0_{CP1}$	$\mathcal{A}^0_{CP2}$
$\mathcal{A}^\perp_{CPJ}$	$\frac{\lvert\overline{A}_{J\perp}\rvert^2/\sum\lvert\overline{A}_{J\lambda}\rvert^2 - \lvert A_{J\perp}\rvert^2/\sum\lvert A_{J\lambda}\rvert^2}{\lvert\overline{A}_{J\perp}\rvert^2/\sum\lvert\overline{A}_{J\lambda}\rvert^2 + \lvert A_{J\perp}\rvert^2/\sum\lvert A_{J\lambda}\rvert^2}$	–	$\mathcal{A}^\perp_{CP1}$	$\mathcal{A}^\perp_{CP2}$
$\Delta\phi_{\parallel J}$	$\frac{1}{2}(\arg(\overline{A}_{J\parallel}/\overline{A}_{J0}) - \arg(A_{J\parallel}/A_{J0}))$	–	$\Delta\phi_{\parallel 1}$	$\Delta\phi_{\parallel 2}$
$\Delta\phi_{\perp J}$	$\frac{1}{2}(\arg(\overline{A}_{J\perp}/\overline{A}_{J0}) - \arg(A_{J\perp}/A_{J0}) - \pi)$	–	$\Delta\phi_{\perp 1}$	$\Delta\phi_{\perp 2}$
$\Delta\delta_{0J}$	$\frac{1}{2}(\arg(\overline{A}_{00}/\overline{A}_{J0}) - \arg(A_{00}/A_{J0}))$	–	$\Delta\delta_{01}$	$\Delta\delta_{02}$

- Overview and definition of the 26 physics parameters
- $\Delta\phi_{00} = \frac{1}{2}\arg(A_{00}/\overline{A}_{00})$ only accessible in $B^0/\overline{B}^0 \to \phi K^0_S \pi^0$

$B^0 \to \phi K^*$ – selection and fit

- Reconstructing $B^0 \to \phi K^*$ with $\phi \to K^+K^-$, $K^* \to K^+\pi^-$
- Cut based selection with neural network (NeuroBayes) based continuum $e^+e^- \to q\bar{q}$ background suppression
- 9D fit to B^0 and $\overline{B}^0$ using the observables

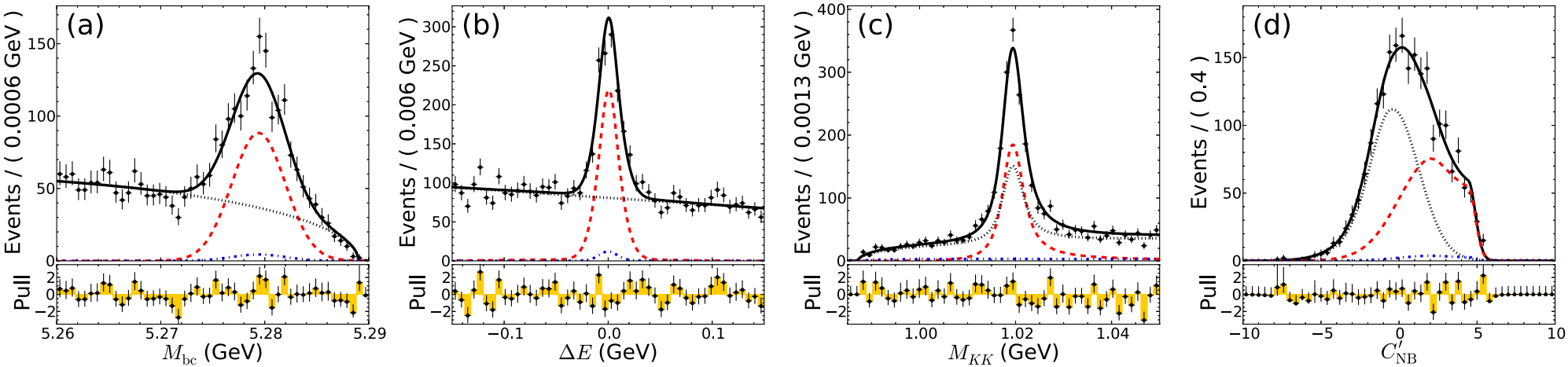
M_{bc}	beam-constrained mass
ΔE	energy difference
M_{KK}	K^+K^- invariant mass
C'_{NB}	continuum suppression network output
$M_{K\pi}$	$K^+\pi^-$ invariant mass
$\phi, \cos\theta_1, \cos\theta_2$	the three helicity angles
Q	charge of primary kaon from B

S/B separation PWA $\not{CP}$

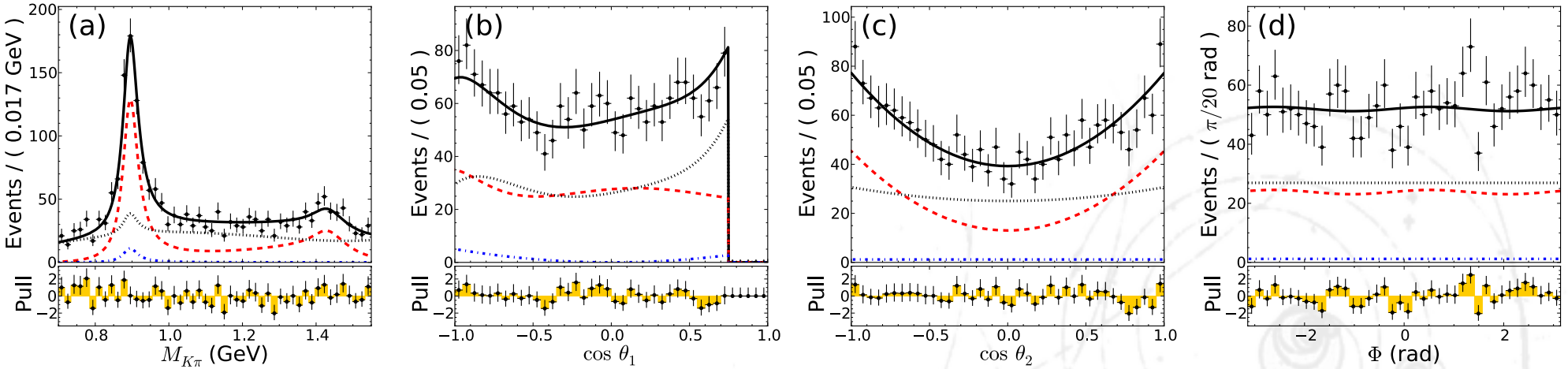
- With three components included in the fit
  - signal
  - peaking background from $B^0 \to f_0(980)K^*(892)^0$
  - continuum background

$B^0 \to \phi K^*$ – fit results (Preliminary)

Total PDF continuum $B^0 \to f_0(980)K^*(892)^0$ $B^0 \to \phi K^*$



Signal enhanced M_{bc} (a), ΔE (b), M_{KK} (c) and C'_{NB} (d) distribution



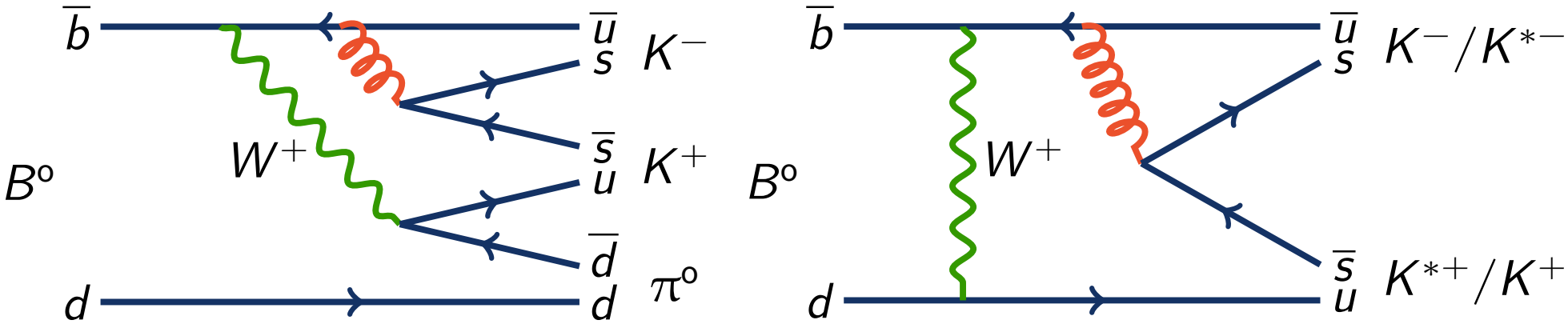
Signal enhanced $M_{K\pi}$ (a), cos θ_1 (b), cos θ_2 (c) and ϕ (d) distributions

$B^0 \to \phi K^*$ – results (Preliminary)

Parameter	$\phi(K\pi)^*_0$ $J=0$	$\phi K^*(892)^0$ $J=1$	$\phi K^*_2(1430)^0$ $J=2$
$\mathcal{B}_J\,(10^{-6})$	$4.3 \pm 0.4 \pm 0.4$	$10.4 \pm 0.5 \pm 0.6$	$5.5^{+0.9}_{-0.7} \pm 1.0$
f_{LJ}	$\cdots$	$0.499 \pm 0.030 \pm 0.018$	$0.918^{+0.029}_{-0.060} \pm 0.012$
$f_{\perp J}$	$\cdots$	$0.238 \pm 0.026 \pm 0.008$	$0.056^{+0.050}_{-0.035} \pm 0.009$
$\phi_{\parallel J}$ (rad)	$\cdots$	$2.23 \pm 0.10 \pm 0.02$	$3.76 \pm 2.88 \pm 1.32$
$\phi_{\perp J}$ (rad)	$\cdots$	$2.37 \pm 0.10 \pm 0.04$	$4.45^{+0.43}_{-0.38} \pm 0.13$
δ_{0J} (rad)	$\cdots$	$2.91 \pm 0.10 \pm 0.08$	$3.53 \pm 0.11 \pm 0.19$
$\mathcal{A}_{CPJ}$	$0.093 \pm 0.094 \pm 0.017$	$-0.007 \pm 0.048 \pm 0.021$	$-0.155^{+0.152}_{-0.133} \pm 0.033$
$\mathcal{A}^0_{CPJ}$	$\cdots$	$-0.030 \pm 0.061 \pm 0.007$	$-0.016^{+0.066}_{-0.051} \pm 0.008$
$\mathcal{A}^\perp_{CPJ}$	$\cdots$	$-0.14 \pm 0.11 \pm 0.01$	$-0.01^{+0.85}_{-0.67} \pm 0.09$
$\Delta\phi_{\parallel J}$ (rad)	$\cdots$	$-0.02 \pm 0.10 \pm 0.01$	$-0.02 \pm 1.08 \pm 1.01$
$\Delta\phi_{\perp J}$ (rad)	$\cdots$	$0.05 \pm 0.10 \pm 0.02$	$-0.19 \pm 0.42 \pm 0.11$
$\Delta\delta_{0J}$ (rad)	$\cdots$	$0.08 \pm 0.10 \pm 0.01$	$0.06 \pm 0.11 \pm 0.02$

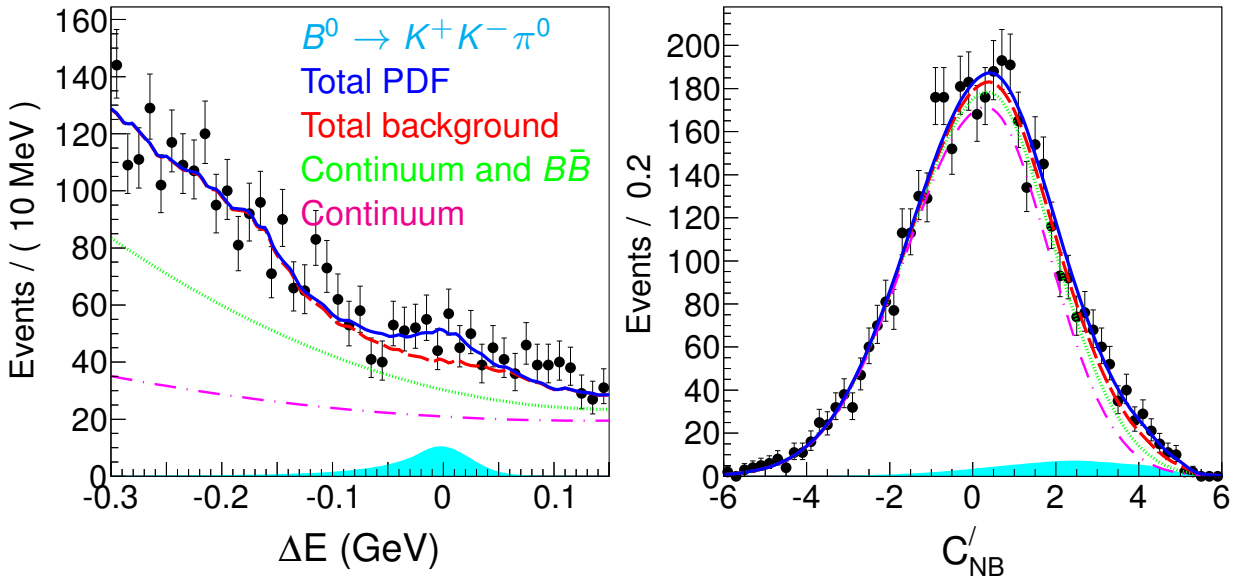
- $\mathcal{B}$ and polarisation parameters consistent with existing results
- Parameters related to direct CP violation consistent with zero

$B^0 \to K^+K^-\pi^0$ – motivation



- Suppressed in the SM $< 1.9 \times 10^{-5}$ CLEO PRL **89**, 251801 (2002)
- Contribution from colour- and Cabibbo-suppressed $b \to u$ tree (*LEFT*) and internal W exchange (*RIGHT*) transitions
- No information on potential resonance modes available
- *BABAR* PRL **99**, 221801 (2007) and LHCb LHCb-CONF-2012-028 observed a structure in the K^+K^- invariant mass around 1.5 GeV/c^2 in $B^+ \to K^+K^-\pi^+$

$B^0 \to K^+K^-\pi^0$ – evidence for the decay

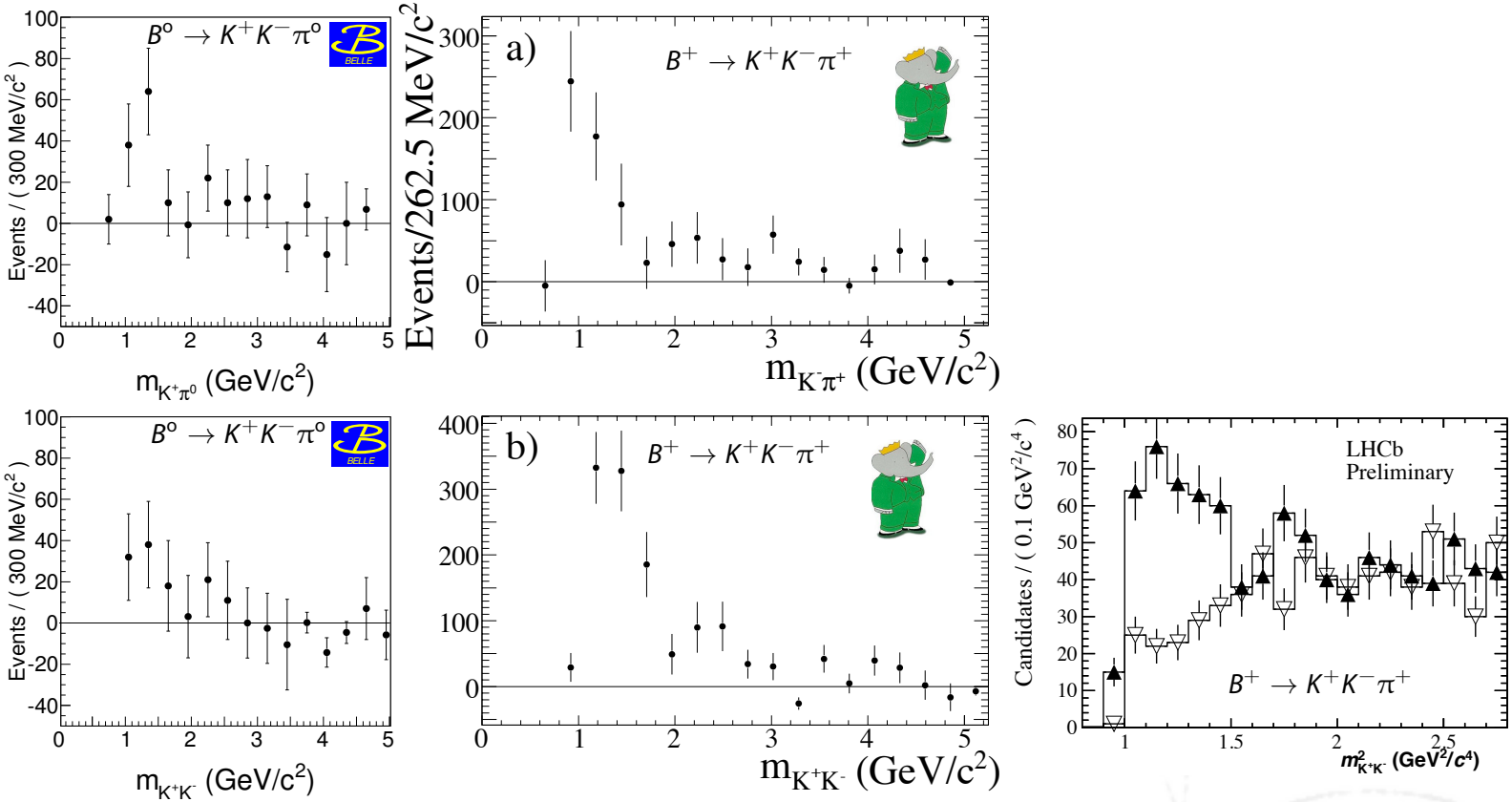


- Cut based selection with neural network (NeuroBayes) based continuum $e^+e^- \to q\bar{q}$ background suppression
- 2D fit of events in the $\pm 3\sigma$ region of beam-constrained B^0 mass
- Fit is using energy difference ΔE and network output C'_{NB}

V. Gaur *et al.* [Belle], PRD **87**, 091101 (2013) **3.5σ**

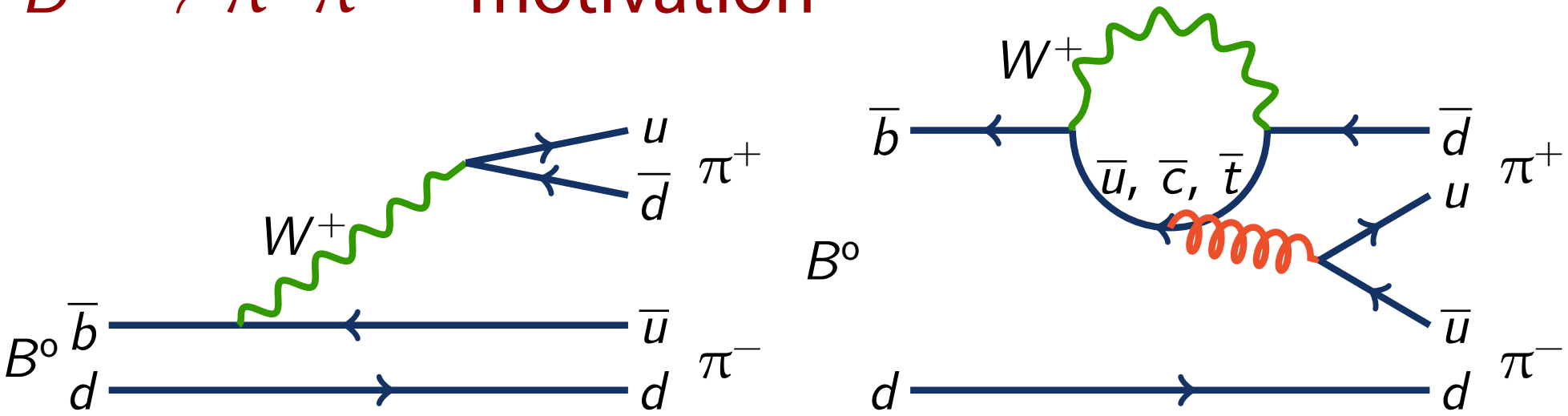
$N_{sig} = 299 \pm 83 \quad \mathcal{B}(B^0 \to K^+K^-\pi^0) = (2.17 \pm 0.60 \pm 0.24) \times 10^{-6}$

$B^0 \to K^+K^-\pi^0$ – resonant substructure



- Signal yield fitted in bins of $m_{K^+K^-}$ and $m_{K^+\pi^0}$
- No definite statement can be made about low-mass structure seen in $m_{K^+K^-}$ by *BABAR* and LHCb
- Excess of events at around $m_{K^+\pi^0} = 1.4\ \mathrm{GeV}/c^2$
- Amplitude analysis and more statistics required → Belle II

$B^0 \to \pi^+\pi^-$ – motivation



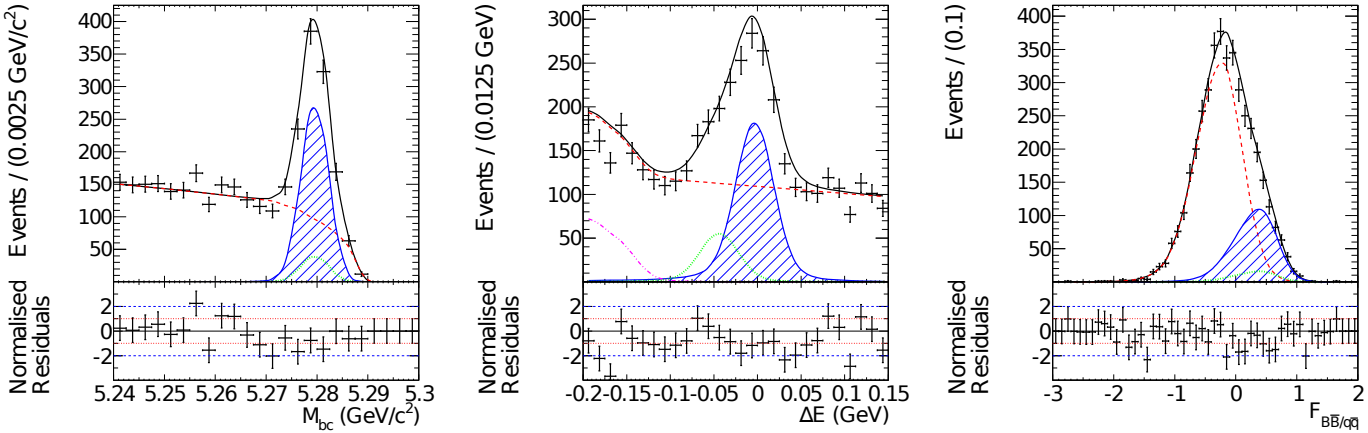
- Decay dominated by $b \to u\bar{u}d$ transitions
- Time evolution:

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \{1 + q\,[\mathcal{A}_{CP} \cos \Delta m_d \Delta t + \mathcal{S}_{CP} \sin \Delta m_d \Delta t]\}$$

- If only tree contribution (*LEFT*) $\to \mathcal{S}_{CP} = \sin 2\phi_2$, however penguin contribution (*RIGHT*) $\mathcal{S}_{CP} = \sqrt{1 - \mathcal{A}_{CP}^2} \sin(2\phi_2 + \Delta\phi_2)$

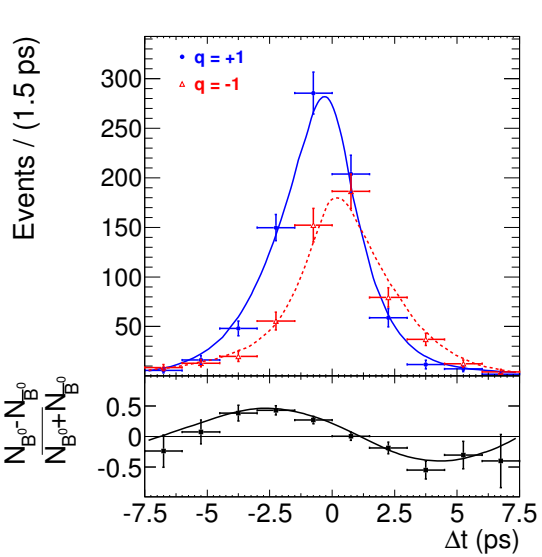
$B^0 \to \pi^+\pi^-$ – analysis and results

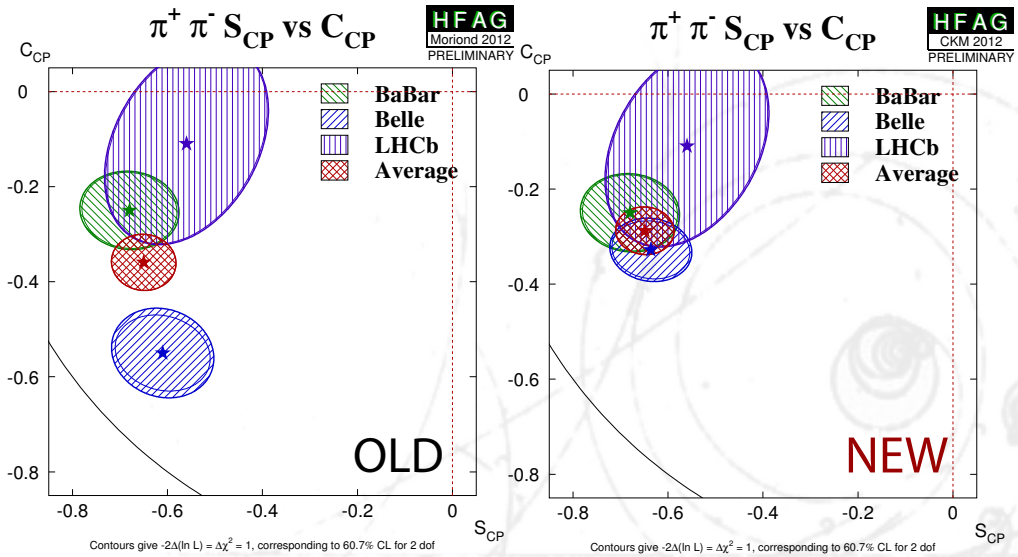
- 9D fit using the observables ΔE, M_{bc}, $\mathcal{L}^+_{K\pi}$, $\mathcal{L}^-_{K\pi}$, $\mathcal{R}_{s/b}$, Δt, q



$$\mathcal{A}_{CP}(B^0 \to \pi^+\pi^-) = +0.33 \pm 0.06 \pm 0.03$$

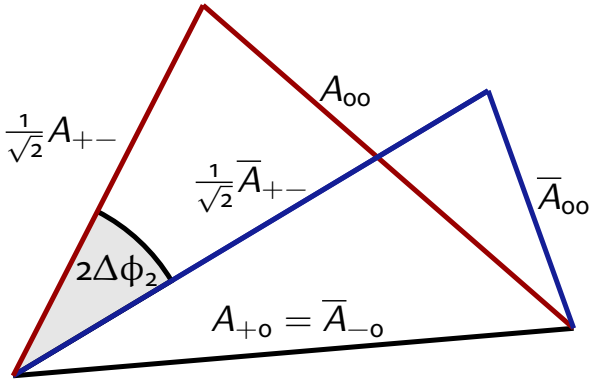
$$\mathcal{S}_{CP}(B^0 \to \pi^+\pi^-) = -0.64 \pm 0.08 \pm 0.03$$





$B^0 \to \pi^+\pi^-$ – results

- determine ϕ_2 with a SU(2) isospin analysis of $B^0 \to \pi\pi$ into all possible charge states M. Gronau, PRL **65**, 3381 (1990)



- Need $\mathcal{S}$, $\mathcal{A}$, $\mathcal{B}$ from $B^0 \to \pi^+\pi^-$, $\pi^0\pi^0$ and $B^+ \to \pi^+\pi^0$

- ϕ_2 isospin analysis of only Belle data

772×10^6 $B^0\overline{B}^0$

- $B^0 \to \pi^+\pi^-$
- $B^+ \to \pi^+\pi^0$

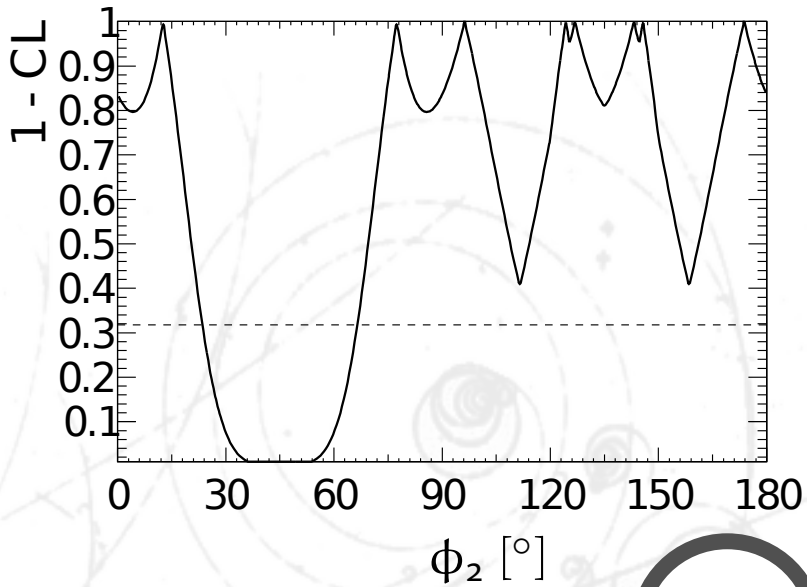
253×10^6 $B^0\overline{B}^0$

- $B^0 \to \pi^0\pi^0$
- updating

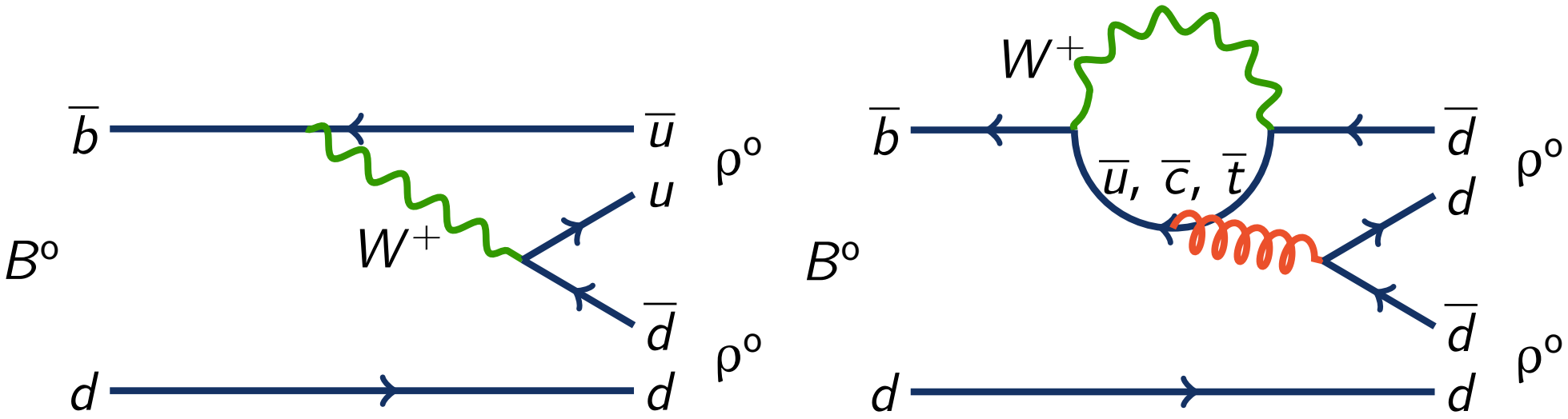
Excluded at 1σ C.L.

$23.8^\circ < \phi_2 < 66.8^\circ$

arXiv:1302.0551 [hep-ex]



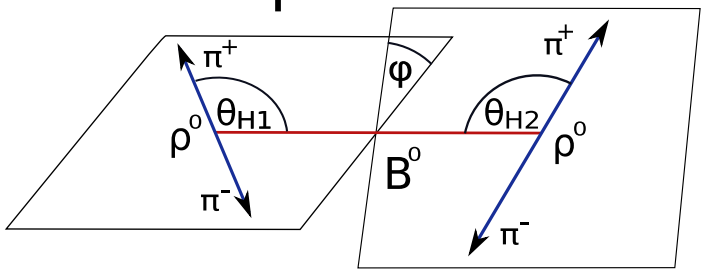
$B^0 \to \rho^0\rho^0$ – motivation



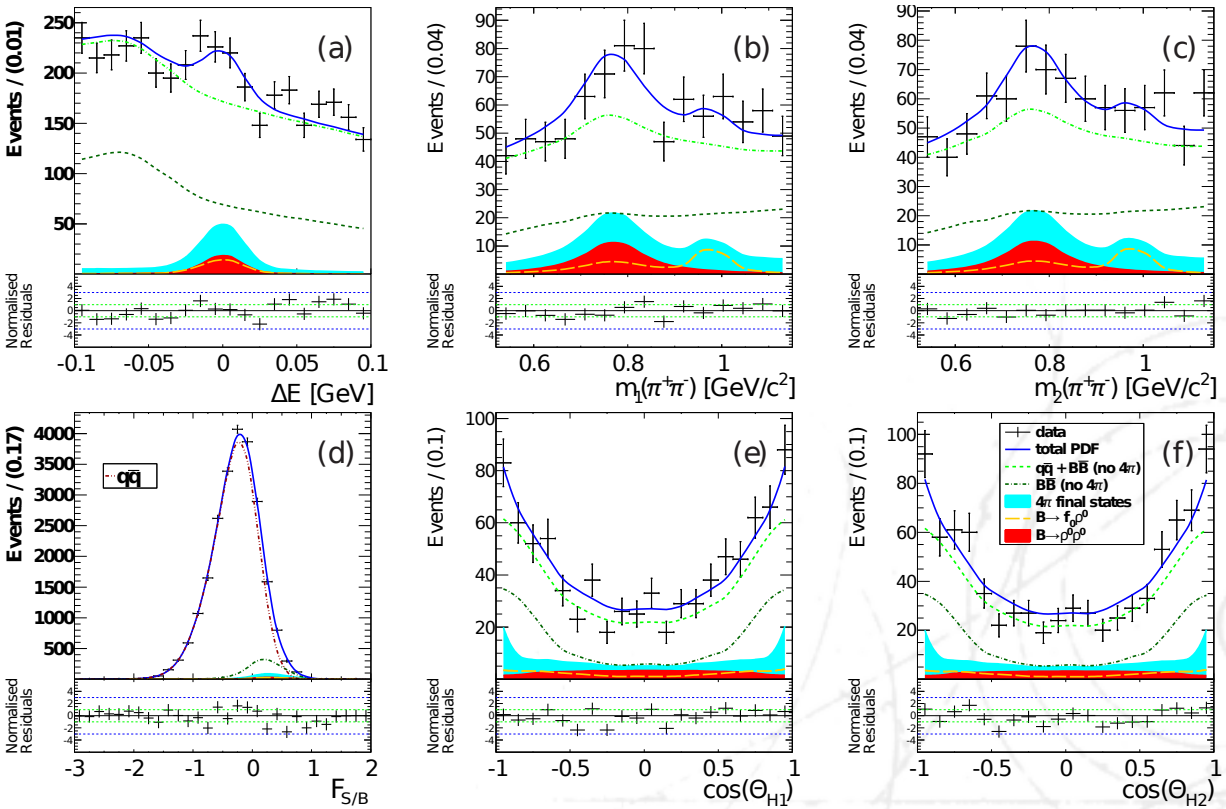
- Decay dominated by $b \to u\bar{u}d$ transitions
  - tree dominated (*LEFT*)
  - color suppressed (*RIGHT*)
- With isospin analysis sensitive to ϕ_2
- $\rho^0\rho^0$ final state is not a pure CP eigenstate
- Longitudinal component CP even, transverse CP odd + even

$B^0 \to \rho^0\rho^0$ – analysis approach

- Helicity analysis to extract polarisation information



- 6D fit using ΔE, $M^1_{\pi^+\pi^-}$, $M^2_{\pi^+\pi^-}$, $\cos\theta^1_H$, $\cos\theta^2_H$, $\mathcal{R}_{s/b}$
- Dominant background $e^+e^- \to q\bar{q}$, large $B^0 \to 4\pi^\pm$



$B^0 \to \rho^0\rho^0$ – results (Preliminary)

I. Adachi *et al.* [Belle], arXiv:1212.4015 — 2.9σ

$$\begin{aligned}\mathcal{B}(B^0 \to \rho^0\rho^0) &= (1.02 \pm 0.30 \pm 0.22) \times 10^{-6} \\ &< 1.5 \times 10^{-6} \text{ at 90\% C.L.}\end{aligned}$$

$$f_L = 0.21^{+0.18}_{-0.22} \pm 0.11$$

- First evidence (3.0σ) for

$$\mathcal{B}(B^0 \to f_0\rho^0) \times \mathcal{B}(f_0 \to \pi^+\pi^-) = (0.86 \pm 0.27 \pm 0.15) \times 10^{-6}$$

- ϕ_2 isospin analysis results

world average

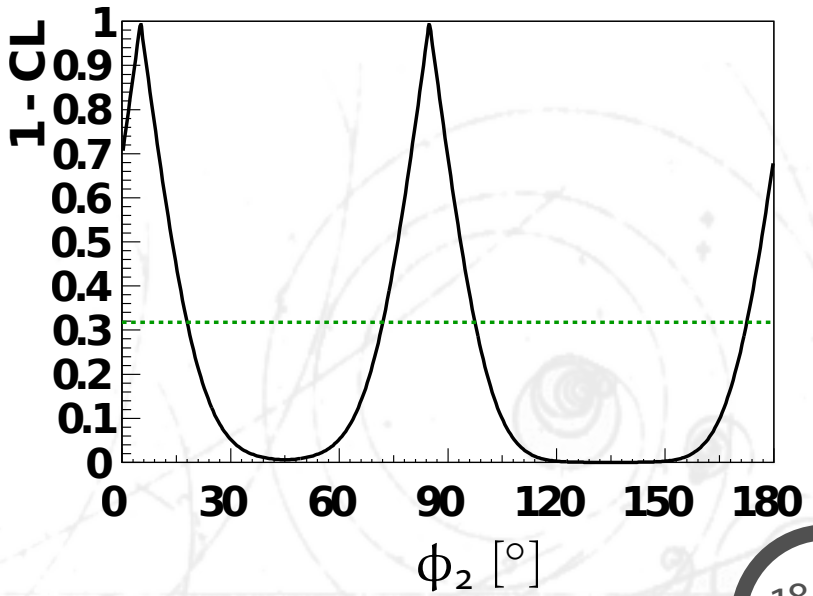
- $\mathcal{B}(B^0 \to \rho^+\rho^-)_L$
- $\mathcal{B}(B^+ \to \rho^+\rho^0)$
- $\mathcal{A}^{+-}$, $\mathcal{S}^{+-}$

BABAR

- $B^0 \to \rho^0\rho^0$
- $\mathcal{A}^{00}$, $\mathcal{S}^{00}$

$$\phi_2 = 91.0^\circ \pm 7.2^\circ$$

$$\Delta\phi_2 = 0.0^\circ \pm 5.4^\circ$$



Summary

- Angular analysis of $B^0 \to \phi K^*$, no evidence for *CP* violation

$$f_L(\phi K_2^*(1430)) = 0.918^{+0.029}_{-0.060} \pm 0.008$$
$$f_L(\phi K^*(892)) = 0.499 \pm 0.030 \pm 0.018$$

- Evidence (3.5σ) for the decay $B^0 \to K^+K^-\pi^0$
  - $\mathcal{B}(B^0 \to K^+K^-\pi^0) = (2.17 \pm 0.60 \pm 0.24) \times 10^{-6}$
- Two measurements that provide new constraints on ϕ_2
  - most precise measurement of CPV in $B^0 \to \pi^+\pi^-$

$$\mathcal{A}_{CP}(B^0 \to \pi^+\pi^-) = +0.33 \pm 0.06 \pm 0.03$$
$$\mathcal{S}_{CP}(B^0 \to \pi^+\pi^-) = -0.64 \pm 0.08 \pm 0.03$$

  - excluding $23.8^\circ < \phi_2 < 66.8^\circ$ (isospin + Belle)
  - measured $B^0 \to \rho^0\rho^0$ at 2.9σ significance
  - $\mathcal{B}(B^0 \to \rho^0\rho^0) = (1.02 \pm 0.30 \pm 0.22) \times 10^{-6}$
  - evidence for $B^0 \to f_0\rho^0$
  - measurement of $\phi_2 = 91.0^\circ \pm 7.2^\circ$ (iso.+Belle+*BABAR*+world)