Measurements of CKM angles at Belle

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On behalf of the Belle Collaboration

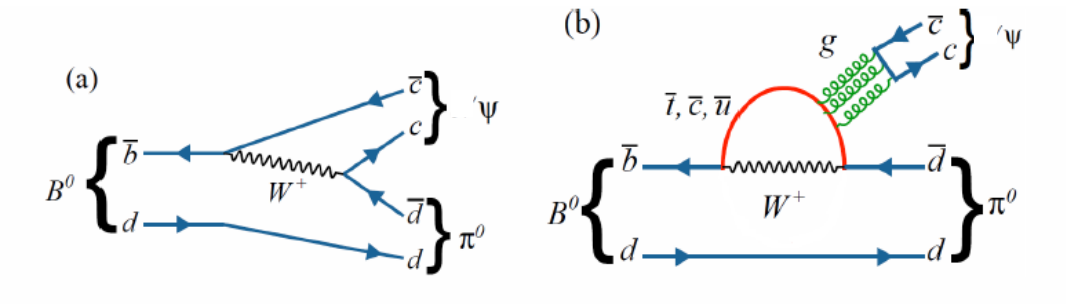
Outline

- $B^0 \to \psi(2S)\pi^0$
- $B^0 \to \underline{D}_{CP} h^0$
- $B^0 \to D^{(*)0} h^0$

} Related to ϕ_1 or β measurement

- $B^0 \to \rho^+\rho^-$ - Related to ϕ_2 or α measurement

$B^0 \to \psi(2S)\pi^0$



- At quark level the decay is proceed via $b \to c\bar{c}d$ transitions, similar to $B^0 \to J/\psi\pi^0$ decays.

- These decays are sensitive to the CP violating angle $\phi_1=\arg(-V_{cd}V^*_{cb}/V_{td}V^*_{tb})$ of the unitarity triangle.
- In the absence of penguin contribution, the direct CP asymmetry A=0 and the mixing-induced CP asymmetry $S=-\sin(2\phi_1)$. The non vanishing A and the deviation of S from $-\sin(2\phi_1)$ arise from the penguin contributions, hence these quantities are useful to probe the Physics beyond the SM.
- These decays are also useful to constrain the penguin pollution in $b \to c\bar{c}s$ transitions. [M. Ciuchini et. al., PRL 95, 221804(2005); S. Faller et.al., PRD 79, 014030(2009); P. Fringe et. al., PRL 115, 061802(2015)]

V. Chobanova et al.,
PRD (R) 93, 031101 (2016)

$B^0 \rightarrow \psi(2S)\pi^0$

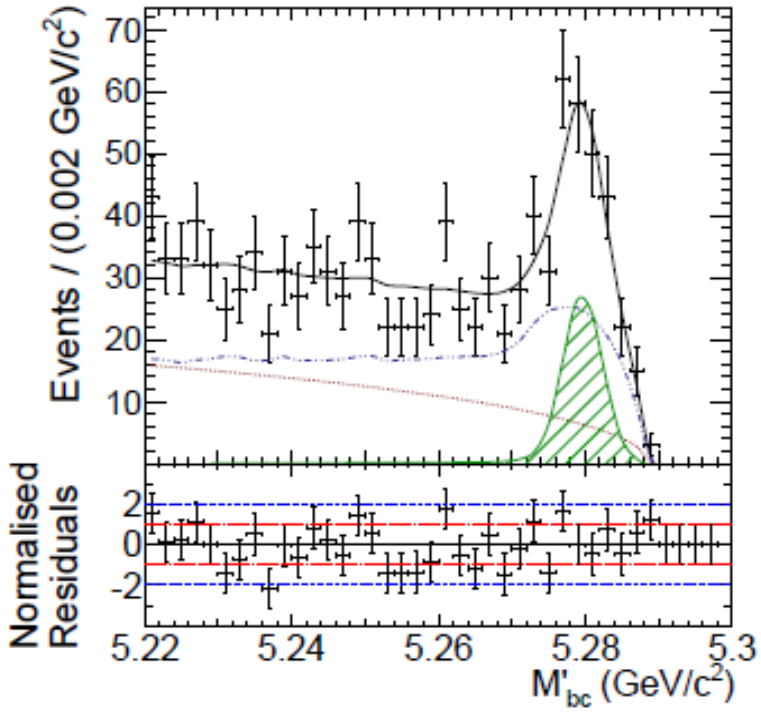
- This Analysis uses full Belle data set of 772×10^6 $B\bar{B}$
- $\Psi(2S)$ is reconstructed from four sub-decays:
  - l^+l^- ($l=e,\mu$)
  - $J/\Psi\pi^+\pi^-$ ($J/\Psi \rightarrow l^+l^-$)
- We include the bremsstrahlung photons that are within 50 mrad of each of electron and positron tracks in e^+e^- modes [both in $\Psi(2S)$ & J/Ψ]
- Vertex- and mass-constraint fits are performed both in $\Psi(2S)$ & J/Ψ and mass-constraint fit is performed in π^0 reconstructions to improve the momentum resolution.
- Continuum background is suppressed by requiring the ratio of second- to zeroth-order Fox-Wolfram moments $R_2<0.5$.
- Modified beam-energy-constrained mass and energy difference are used in 2D fit procedure.

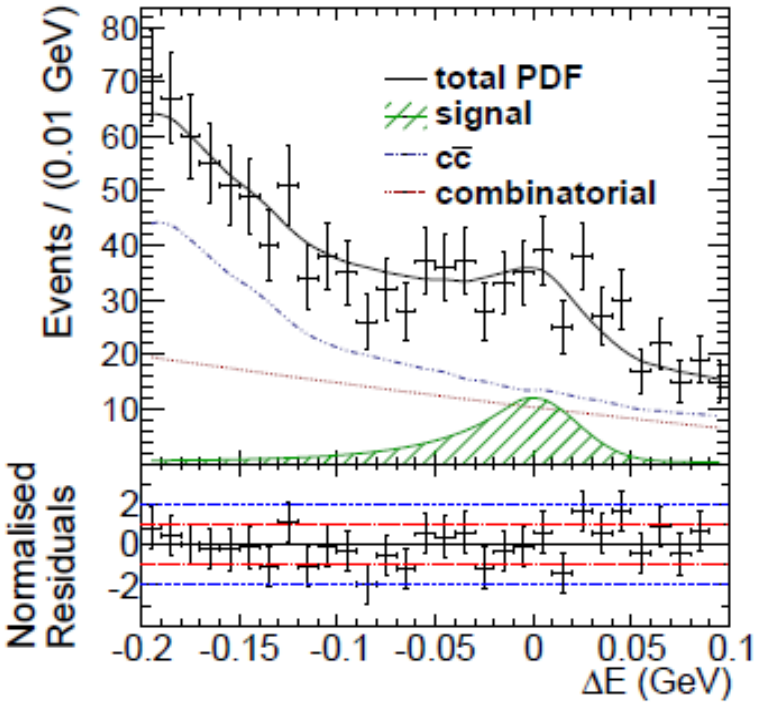
$\Delta E = E_B - E_{beam}$,

$$M'_{bc} \equiv \sqrt{(E_{beam})^2 - \left|\vec{p}_{\psi(2S)} + \sqrt{(E_{beam} - E_{\psi(2S)})^2 - m^2_{\pi^0}}\,\frac{\vec{p}_{\pi^0}}{|\vec{p}_{\pi^0}|}\right|^2},$$

- All four sub-decay modes for $\Psi(2S)$ are combined for the branching fraction measurement.

$B^0 \rightarrow \psi(2S)\pi^0$



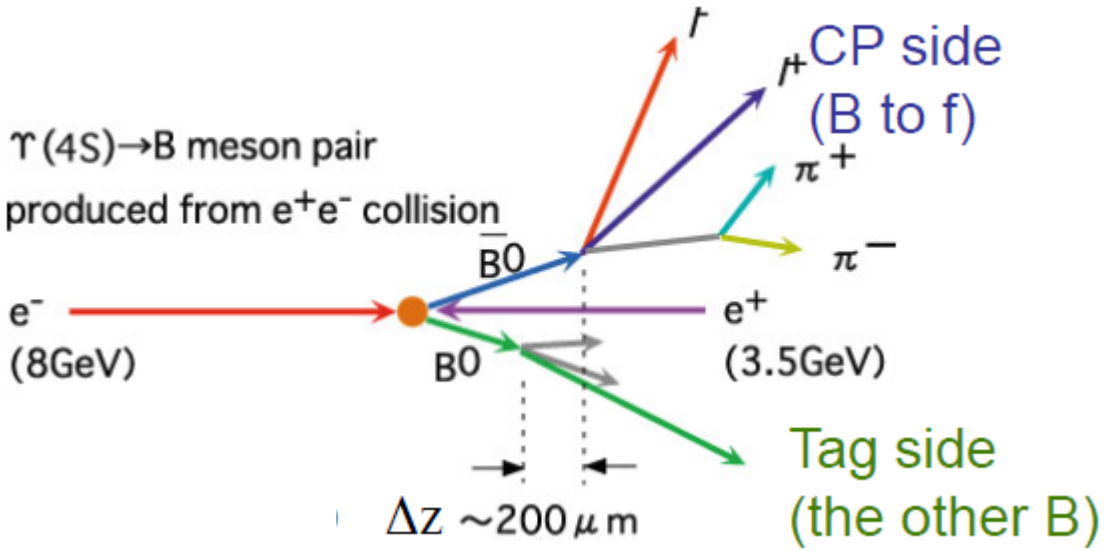


- Observed signal yield = 85±12 with a significance of 7.2σ including the systematic uncertainty (First observation)
- $\mathcal{B}(B^0 \rightarrow \psi(2S)\pi^0)=[1.17\pm0.17(stat)\pm0.08(syst)]\times10^{-5}$.
- No CPV measurement yet for this mode.

Time-dependent CPV

$$\Delta t = \frac{\Delta z}{\beta\gamma c}$$

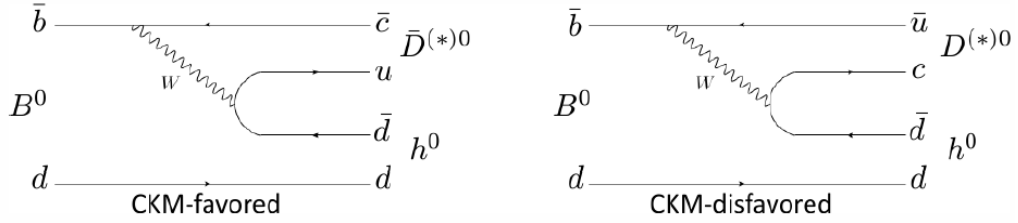
$\beta\gamma$=0.425



$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to f) - \Gamma(B^0(\Delta t) \to f)}{\Gamma(\overline{B}^0(\Delta t) \to f) + \Gamma(B^0(\Delta t) \to f)} = \mathcal{S}_f \sin(\Delta m_d \Delta t) + \mathcal{A}_f \cos(\Delta m_d \Delta t)$$

$B^0 \rightarrow D_{CP} h^0$

- The decay is mediated via the tree-level diagram (penguin pollution free)

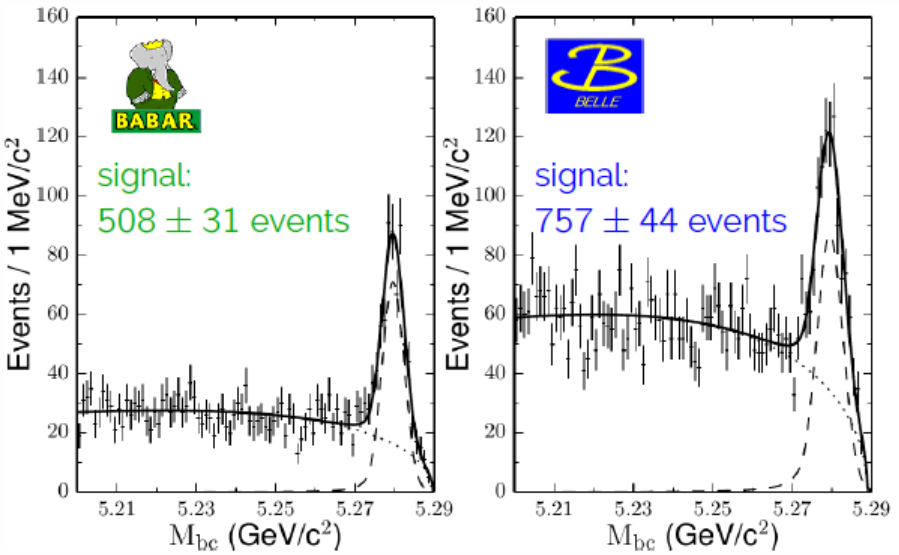


Belle + BaBar Joint Analysis

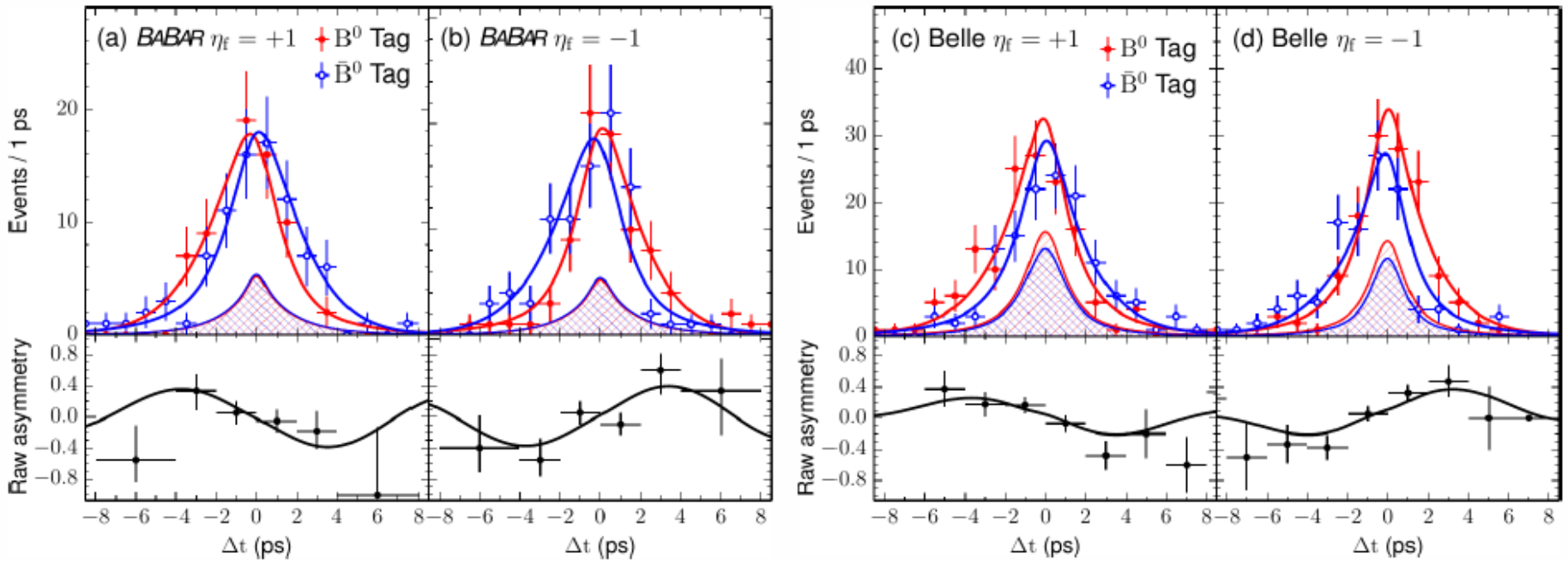
A. Abdesselam *et. al.*, PRL 115, 121604 (2015)

- CPV parameter $\sin(2\phi_1)$ could be accessed, complementary to the measurement from b→ccs transitions.
- Total 12 modes reconstructed with $D^0 \rightarrow K^+K^-$, $K_S\pi^0$, $K_S\omega$; $D^{*0} \rightarrow D^0\pi^0$ and $h^0 = \eta, \omega, \pi^0$
- Neural Network is used to reduce the dominant continuum background
- 1D unbinned fit to the variable M_{bc} in order to extract the signal yield.

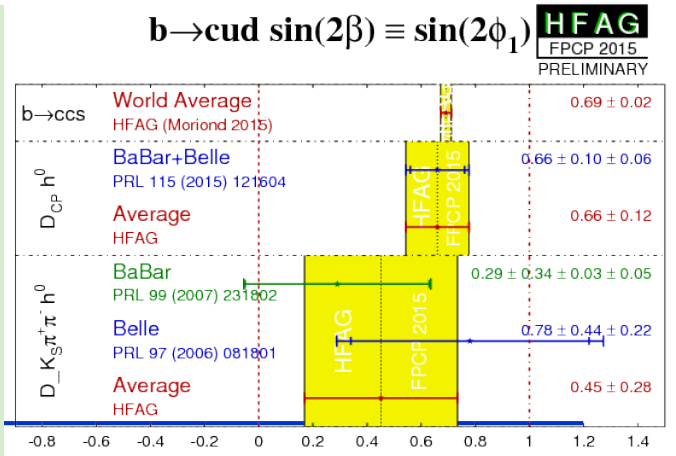
Decay mode	*BABAR*	Belle
$\bar{B}^0 \rightarrow D_{CP}\pi^0$	241 ± 22	345 ± 25
$\bar{B}^0 \rightarrow D_{CP}\eta$	106 ± 14	148 ± 18
$\bar{B}^0 \rightarrow D_{CP}\omega$	66 ± 10	151 ± 17
$\bar{B}^0 \rightarrow D^*_{CP}\pi^0$	72 ± 12	80 ± 14
$\bar{B}^0 \rightarrow D^*_{CP}\eta$	39 ± 8	39 ± 10
$\bar{B}^0 \rightarrow D^{(*)}_{CP}h^0$ total	508 ± 31	757 ± 44



$B \rightarrow D_{CP} h^0$



- The time-dependent measurement is performed analyzing simultaneously the final data samples of Belle & BaBar experiments collected at Y(4S) resonance ~ 1.1 /ab
- $-\eta_f S = 0.66 \pm 0.10 \pm 0.06$ (5.4 σ non-zero CP violation, in agreement with the CPV parameters in b→ccs) → first observation of CPV in this decay
- $C = -A = -0.02 \pm 0.07 \pm 0.03$ (no evidence for direct CPV)



$B^0 \to \bar{D}^{(*)0} h^0$

- Similar to $B \to D_{CP} h^0$, but $\bar{D}^0 \to K_S \pi^+ \pi^-$ is not a CP eigenstate, rather mixture of CP eigenstate $K_S \rho^0$, flavor specific $K^{*+}\pi^-$ and $K^{*-}\pi^+$
  - Standard time-dependent CP measurement does not work
    - Model independent measurement of ϕ_1 in $b \to cud$ transitions using a binned Dalitz plot technique (first time for the ϕ_1 measurement)
    - Binned Dalitz distribution approach is originally proposed for ϕ_3 measurements by A. Giri *et. al.* [PRD 68, 054018 (2003)]

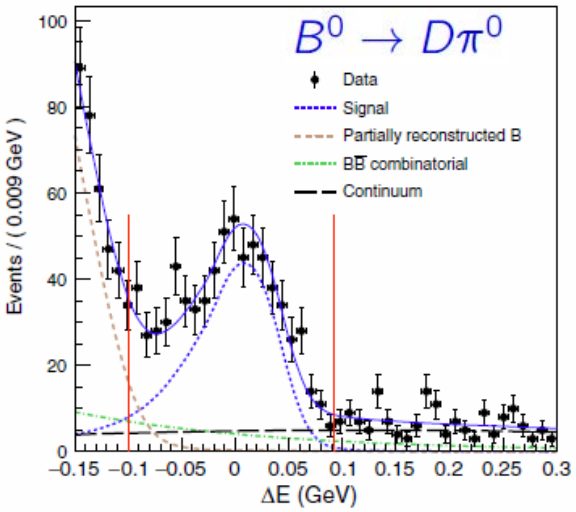
This approach is sensitive to ϕ_1 or both $\sin 2\phi_1$ and $\cos 2\phi_1$.

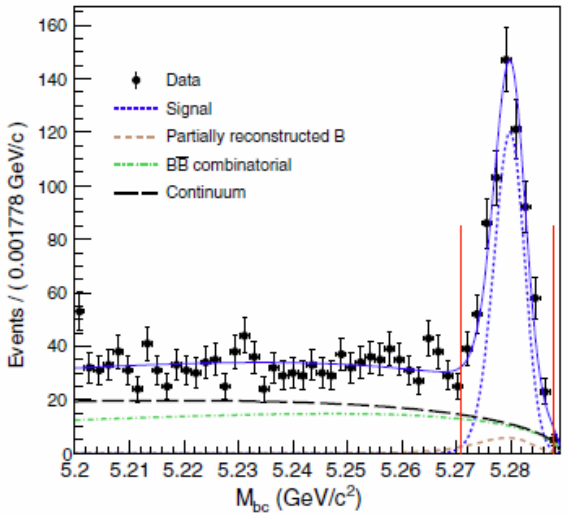
V. Vorobyev et al.,
PRD 94, 052004 (2016)

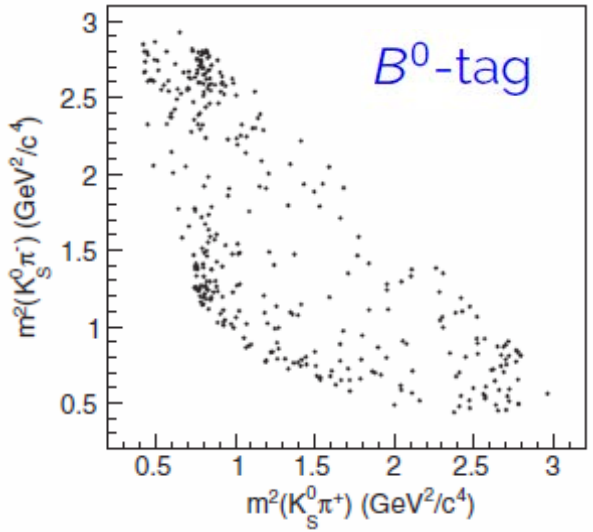
$B^0 \to D^{(*)0} h^0$

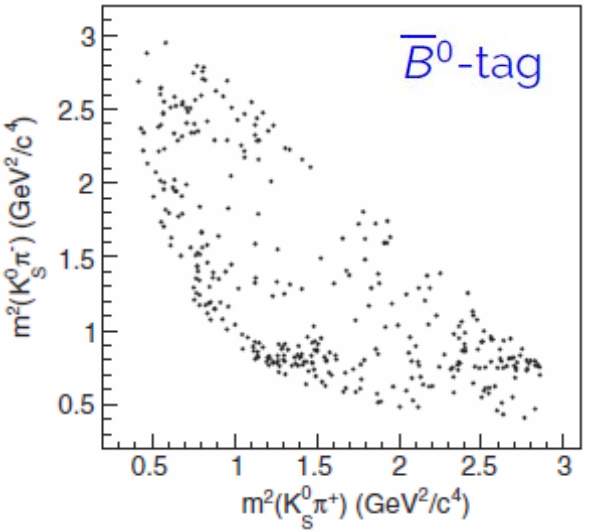
- Standard 2D fit to M_{bc} & ΔE
- f_{sig} used in the fit of the CPV parameter.

Mode	N_{sig}	f_{sig} (%)
$B^0 \to \bar{D}^0 \pi^0$	464 ± 26	72.1 ± 4.1
$B^0 \to \bar{D}^0 \eta_{\gamma\gamma}$	99 ± 14	50.5 ± 7.0
$B^0 \to \bar{D}^0 \eta_{\pi^+\pi^-\pi^0}$	51.3 ± 8.8	66 ± 11
$B^0 \to \bar{D}^0 \omega$	182 ± 18	58.4 ± 5.7
$B^0 \to \bar{D}^0 \eta'$	28.2 ± 6.4	70 ± 16
$B^0 \to \bar{D}^{*0} \pi^0$	103 ± 17	44.1 ± 7.4
$B^0 \to \bar{D}^{*0} \eta$	36.1 ± 7.6	64 ± 13
Total	962 ± 41	61 ± 2.6









$B^0 \rightarrow D^{(*)0} h^0$

Complicated Signal PDF (TD binned analysis):

$$\mathcal{P}_i(\Delta t, \varphi_1) = h_2 e^{-\frac{|\Delta t|}{\tau_B}} \Big[1 + q_B \frac{K_i - K_{-i}}{K_i + K_{-i}} \cos(\Delta m_B \Delta t) + 2 q_B \xi_{h^0} (-1)^L \frac{\sqrt{K_i K_{-i}}}{K_i + K_{-i}} \sin(\Delta m_B \Delta t) \times (S_i \cos 2\varphi_1 + C_i \sin 2\varphi_1) \Big],$$

Where

- The Dalitz probability K_i is obtained from the control sample $B^+ \rightarrow \overline{D}^0 \pi^+$
- The strong phase parameters S_i and C_i are from coherent decay of $D^0\overline{D}^0$ pairs by CLEO [PRD 82, 112006(2006)]

mode	$\sin 2\phi_1$	$\cos 2\phi_1$
$B^0 \rightarrow D\pi^0$	0.61 ± 0.37	$0.88^{+0.46}_{-0.52}$
$B^0 \rightarrow D\omega$	-0.12 ± 0.58	$1.28^{+0.62}_{-0.69}$
others	0.44 ± 0.51	$0.89^{+0.49}_{-0.55}$
combined	$0.43 \pm 0.27 \pm 0.08$	$1.06 \pm 0.33^{+0.21}_{-0.15}$

$\phi_1 = 11.7^\circ \pm 7.8^\circ \pm 2.1^\circ$

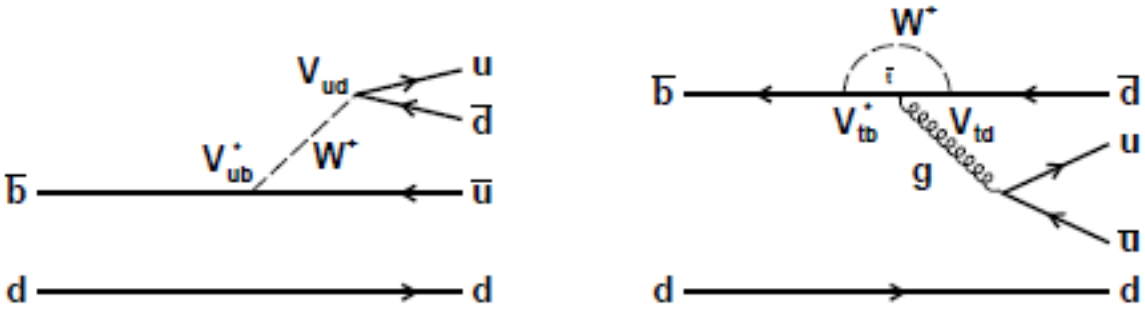
The value $\sin 2\phi_1 = 0.691 \pm 0.017$ in $b \rightarrow ccs$ golden mode gives two solutions

- $\phi_1 = 21.9^\circ$ (1.3 standard deviations away)
- $\phi_1 = 68.1^\circ$ (5.1 standard deviations away)

Our result definitely disfavored the second solutions obtained from the golden mode

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

- Mixing-induced CPV in this decay is sensitive to the parameter $\phi_2 = arg(-\frac{V_{td}V_{tb}^*}{V_{ub}V_{ud}^*})$



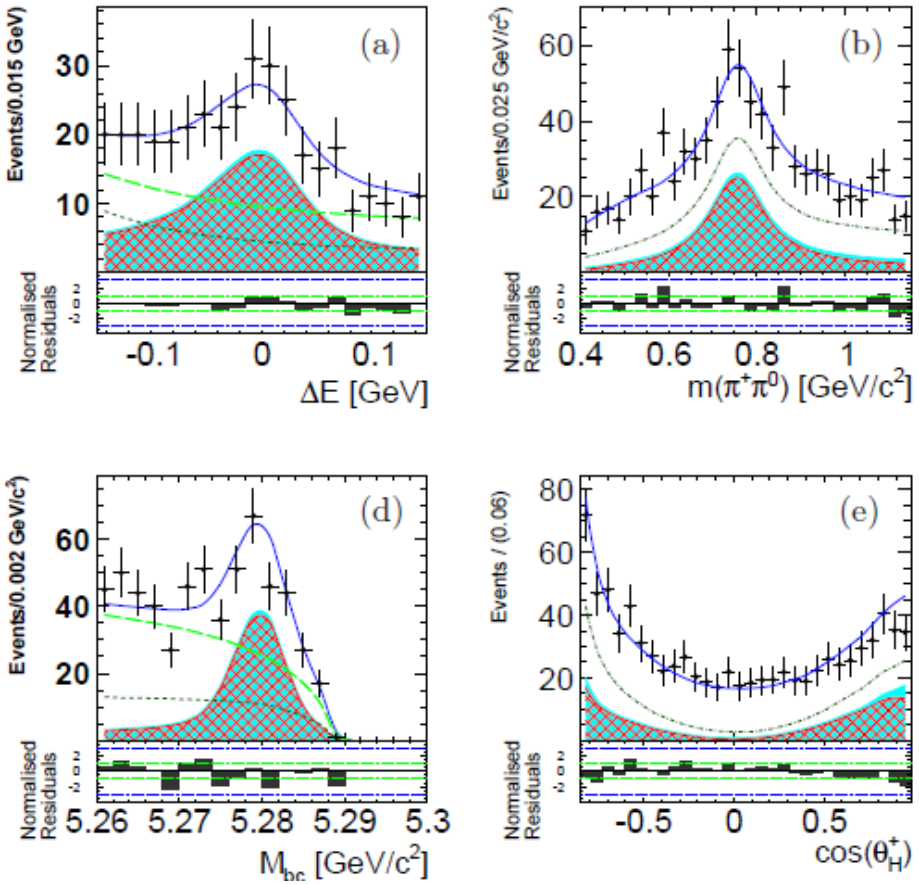
- If tree only, then S_f is directly connected to $\sin(2\phi_2)$ and $A_f=0$
- Penguin contribution shift the measured angle to $\phi_2^{eff} = \phi_2 + \Delta\phi_2$; $\Delta\phi_2$ can be extracted from an isospin analysis or SU(3) flavor symmetry.

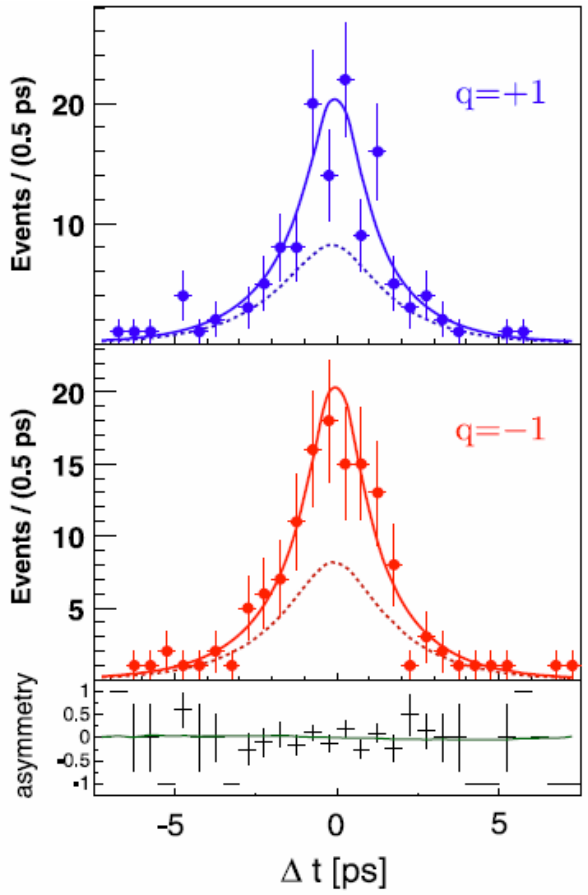
- Previous Belle publication with 535×10^6 BB [PRD 76, 011104 (2007)]
- This analysis uses full set of Belle Data
- Fisher discriminant is used to reduce the continuum background

P. Vanhoefer *et. al.*, PRD 93, 032010 (2016)

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

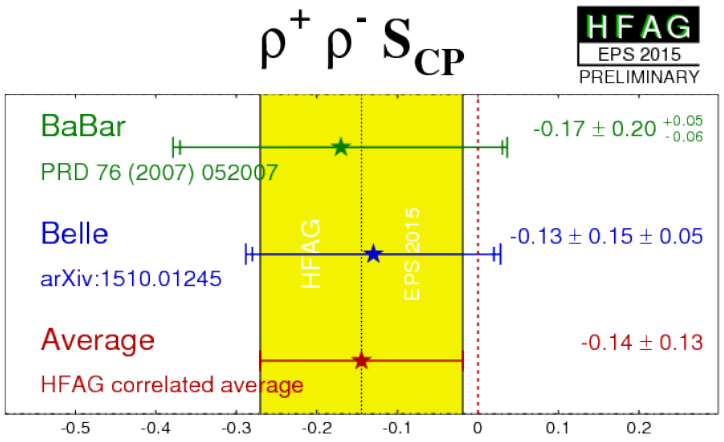
9D MLH fit to $\Delta E, M_{bc}, \mathcal{F}_{S/B}, m_1(\pi^+\pi^0), m_2(\pi^-\pi^0), \cos\theta_{\rm H}^+, \cos\theta_{\rm H}^-, \Delta t, q$

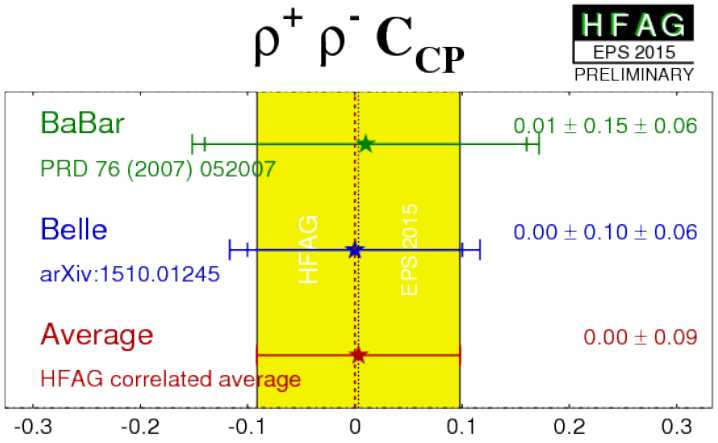




$B^0 \to \rho^+\rho^-$

$$\begin{aligned}
\mathcal{B}(B^0 \to \rho^+\rho^-) &= (28.3 \pm 1.5\ (\text{stat}) \pm 1.5\ (\text{syst})) \times 10^{-6}, \\
f_L &= 0.988 \pm\ 0.012\ (\text{stat}) \pm 0.023\ (\text{syst}), \\
\mathcal{A}_{CP} &= 0.00 \pm 0.10\ (\text{stat}) \pm 0.06\ (\text{syst}), \\
\mathcal{S}_{CP} &= -0.13 \pm 0.15\ (\text{stat}) \pm 0.05\ (\text{syst}).
\end{aligned}$$

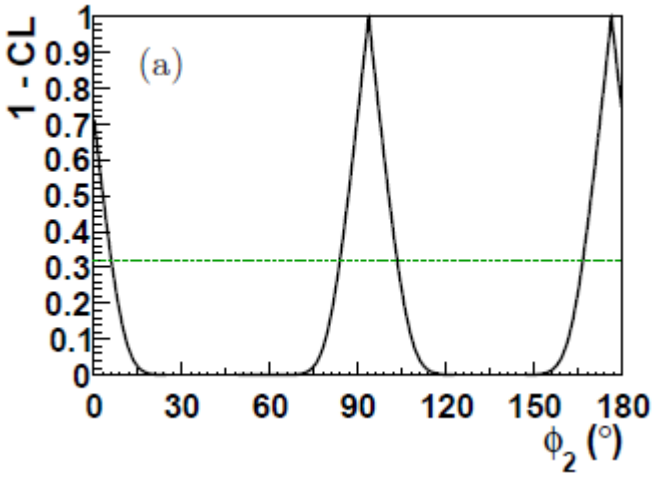




These are the most precise measurements to date for this decay mode. An improvement of a factor of 2 is achieved compared to previous Belle analysis.

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

Isospin analysis is performed with inputs also from Belle's $\rho^0\rho^+$ and $\rho^0\rho^0$ measurements.[PRD 89,072008 (2014); PRL 91, 221801(2003)]



- Two solutions are found, one consistent with SM is (93.7±10.6) deg.
- Also the size of penguin contribution is consistent with zero, (0.0±9.6) deg

- BaBar: $\alpha = (92.4\ ^{+6.0}_{-6.5})°$

Summary

- First observation of the decay $B^0 \rightarrow \psi(2S)\pi^0$ is presented, this decay mode can be used in future to measure ϕ_1
- First observation of CPV in $B \rightarrow D_{CP}h^0$ is presented using BaBar + Belle joint analysis, which was not possible without combining.
- Result of model-independent time-dependent binned Dalitz plot for $B \rightarrow D^{(*)0}h^0$ is presented.
- ϕ_2 from $B \rightarrow \rho\rho$ decays is presented

- But that's not all – Belle still has number of analyses in preparation for ϕ_1 and ϕ_2 measurements
- Many years after it's shutdown Belle still producing interesting results and expecting many more from the upcoming Belle II
- Specially, modes with h^0 are more interesting with Belle II statistics which may not be so easy by LHCb