Experimental review on the UT angles $\alpha(\phi_2)$ and $\beta(\phi_1)$

Fabio Anulli

INFN Sezione di Roma

on behalf of the BABAR Collaboration

Flavor Physics and *CP* Violation

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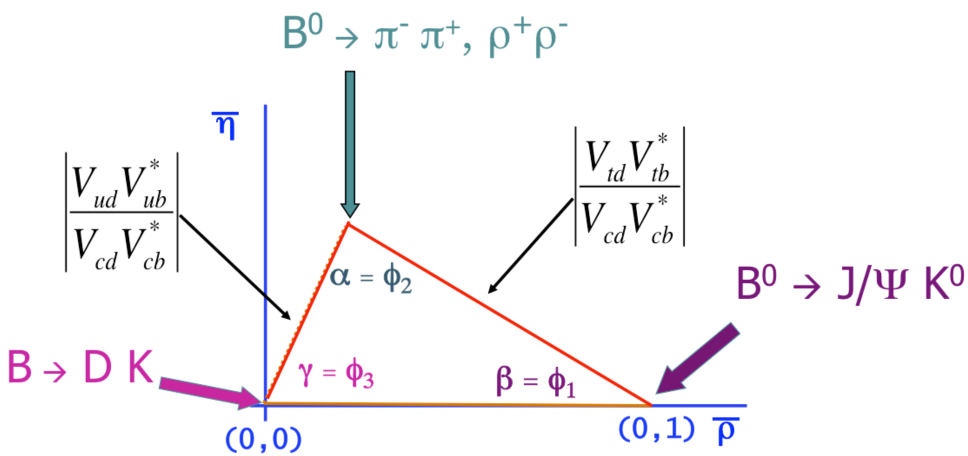
The CKM matrix and the Unitarity Triangle

$$V_{CKM} = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array} + O(\lambda^4)$$

- Describes the quark mixing in weak charged transitions
- The CKM is unitary
- 3 real parameters A, ρ, λ and 1 phase η ➠ V_{ij} are complex
- Interfering amplitudes can give *CP* violating asymmetries
- The CKM is the only source of *CPV* in the SM

Unitarity relation: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

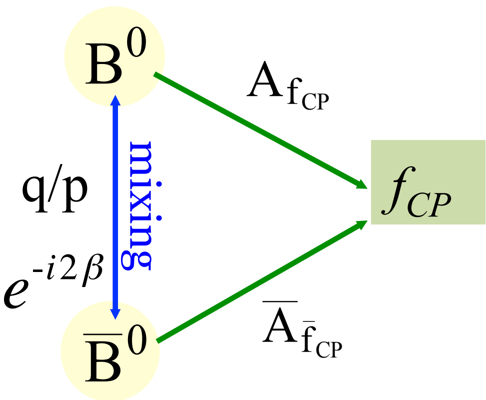
➠ It is a Triangle in the complex plane with angles related to CKM matrix elements



- Measurements at *B* factories (but not only) can over-constrain the UT
- New Physics would be revealed in discrepancies among measurements

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \qquad \alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \qquad \gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Time-dependent *CP* asymmetries



- *CP* violation arises from interference between the two paths (decay with and without mixing)

Independent of phase convention

$$\lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

Decay amplitude ratio

Phase factor due to mixing

Condition for CPV:

$$\boxed{\lambda_{f_{CP}} \neq \pm 1 \iff \Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) \neq \Gamma(B^0_{phys}(t) \to f_{CP})}$$

Time dependent *CP* asymmetry:

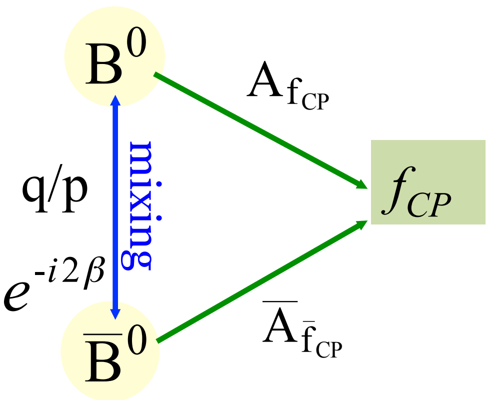
Mixing-induced CPV ***Direct CPV***

$$A_{CP}(t) = \frac{\Gamma\left(\bar{B}^0(t) \to f_{CP}\right) - \Gamma\left(B^0(t) \to f_{CP}\right)}{\Gamma\left(\bar{B}^0(t) \to f_{CP}\right) + \Gamma\left(B^0(t) \to f_{CP}\right)} = S_{f_{CP}} \sin\left(\Delta m t\right) - C_{f_{CP}} \cos\left(\Delta m t\right)$$

$$C_{f_{CP}} = \frac{1 - \left|\lambda_{f_{CP}}\right|^2}{1 + \left|\lambda_{f_{CP}}\right|^2}$$

$$S_{f_{CP}} = \frac{-2\, Im\lambda_{f_{CP}}}{1 + \left|\lambda_{f_{CP}}\right|^2}$$

Time-dependent *CP* asymmetries



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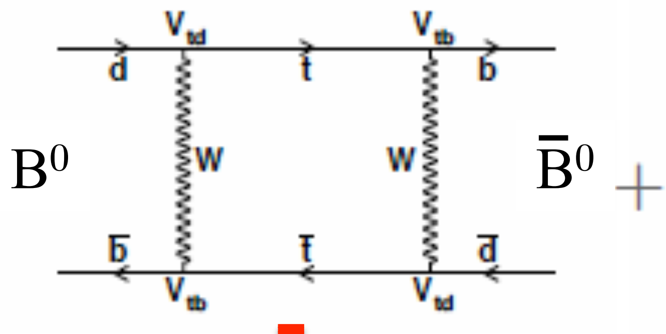
$$S_{f_{CP}} = \frac{-2\, Im \lambda_{f_{CP}}}{1 + \left|\lambda_{f_{CP}}\right|^2}$$

$$\left|\frac{q}{p}\right| \cong 1 \text{ if also } \left|\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}\right| \cong 1 \quad \Rightarrow \quad \lambda_{f_{CP}} = e^{2i\phi} \quad \Rightarrow \quad \boxed{\begin{aligned} C_{f_{CP}} &= 0 \\ S_{f_{CP}} &= -\eta_f \sin 2\phi \end{aligned}}$$

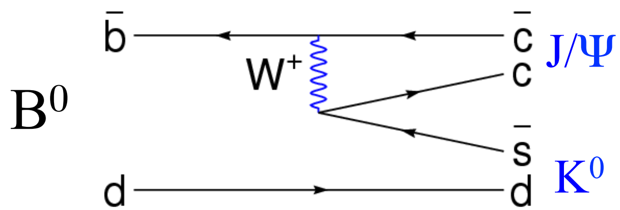
β/ϕ_1

Measuring β in $b \to c$ transitions

- The angle β can be experimentally accessed exploiting the interference between B^0-$\bar{B}^0$ box diagram (phase 2β) and $b \to c$ decay amplitudes (no weak phase)
- Not all $b \to c$ decays are equivalent!

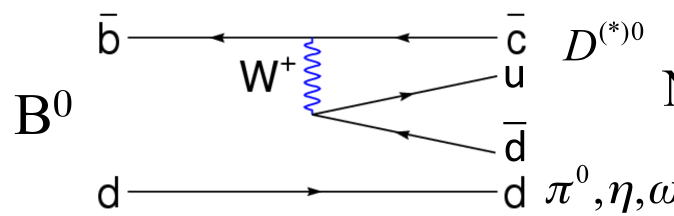


$$e^{-i2\beta}$$



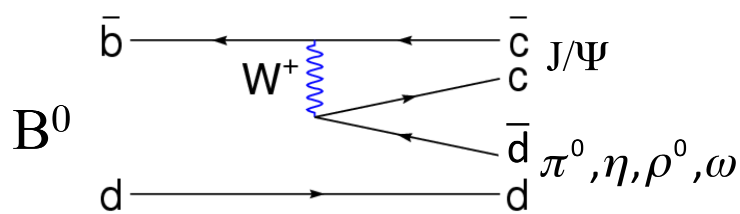
$b \to c\bar{c}s$

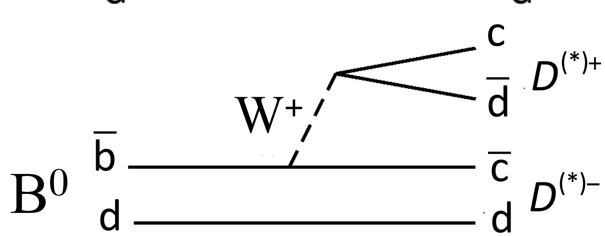
The golden modes



$b \to c\bar{u}d$

No penguin pollution.
Benchmark for SM.



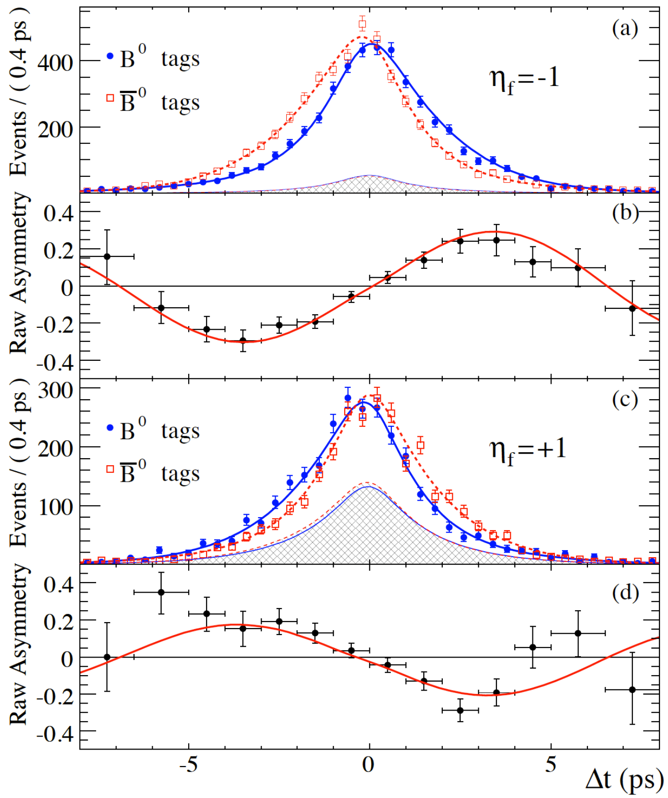


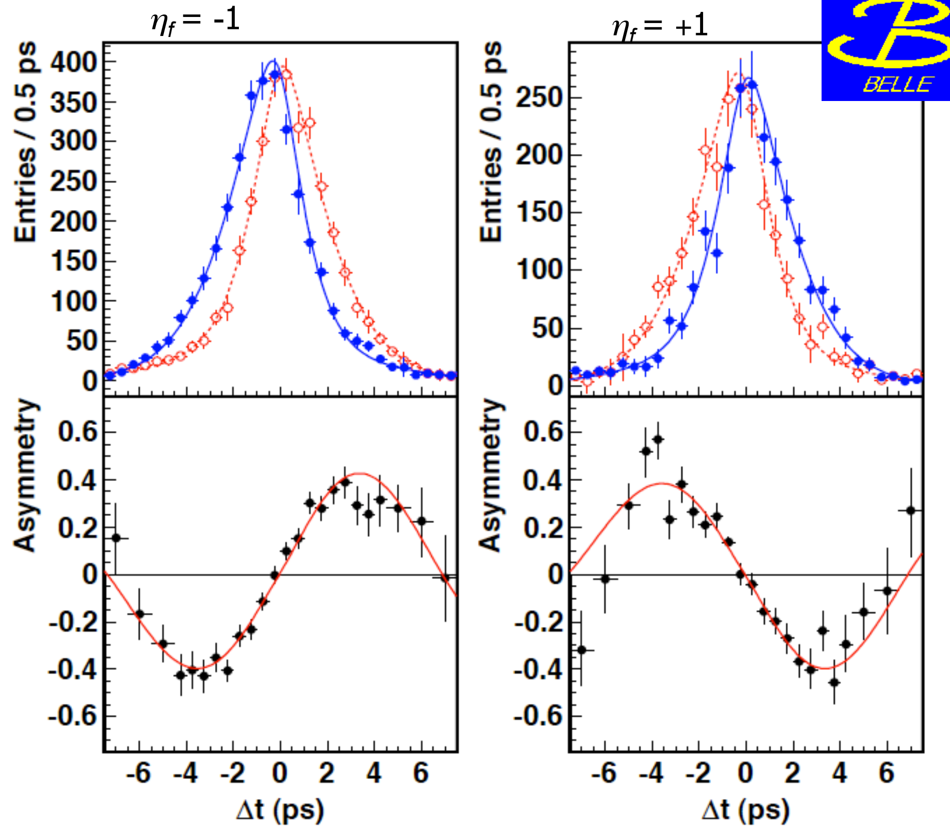
$b \to c\bar{c}d$

Constraints for penguin pollution.
Search for NP.

sin2β from $b \to c\bar{c}s$

- BABAR and Belle established *CPV* in the B system, and brought the precision of the measurements of sin2β down to 3% ($\sigma_\beta < 1^o$)





BABAR, PRD 79, 072009 (2009)

S = 0.687 ± 0.028 ± 0.012

C = 0.024 ± 0.020 ± 0.016

Belle, PRL 108, 171802 (2012)

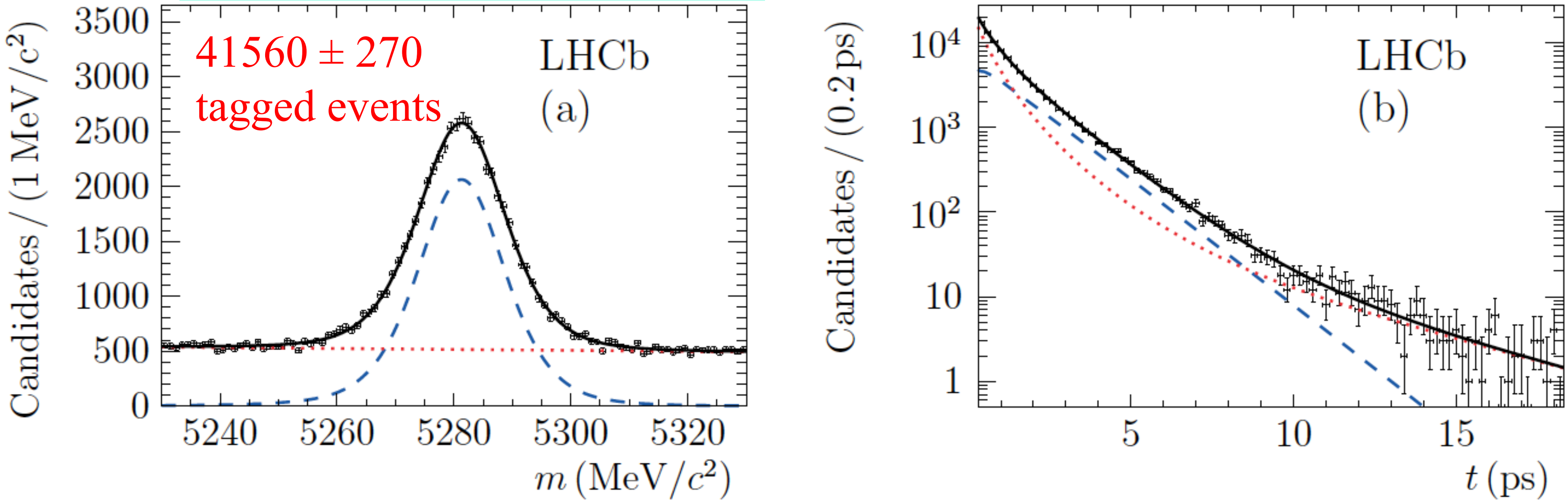
S = 0.667 ± 0.023 ± 0.012

C = -0.006 ± 0.016 ± 0.012

$\sin 2\beta$ from $B^0 \to J/\psi\, K_S$ by LHCb

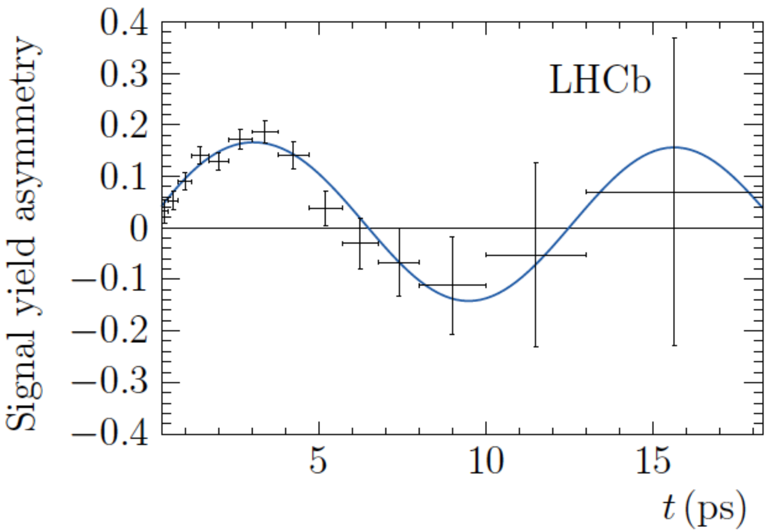
- Run1 data set of 3.1 fb^{-1}
- Reconstruct $J/\psi \to \mu^+\mu^-$ and $K_S \to \pi^+\pi^-$
- Very large statistics
- Excellent resolution on proper-time measurement (~60 fs)
- Effective tagging efficiency of $(3.02 \pm 0.02)\%$

LHCb, PRL 115, 031601 (2015)



sin2β from $B^0 \to J/\psi K_S$ by LHCb

- Measured asymmetry

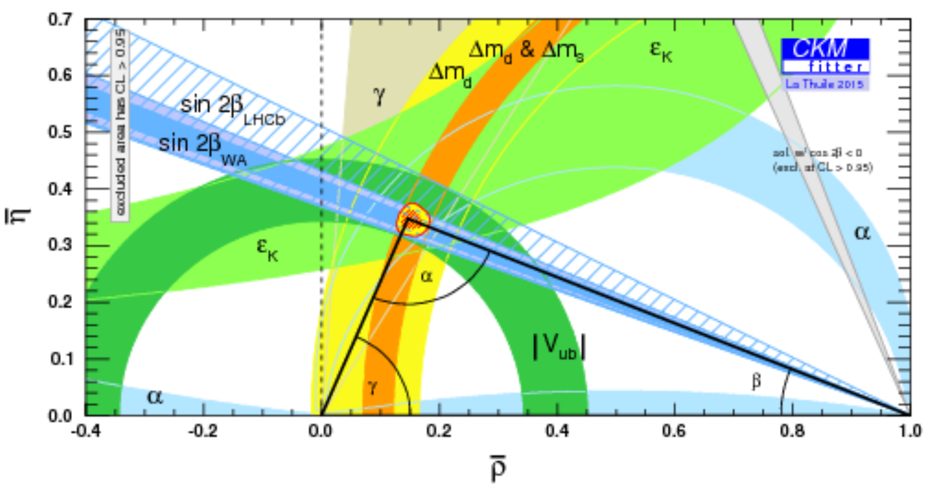


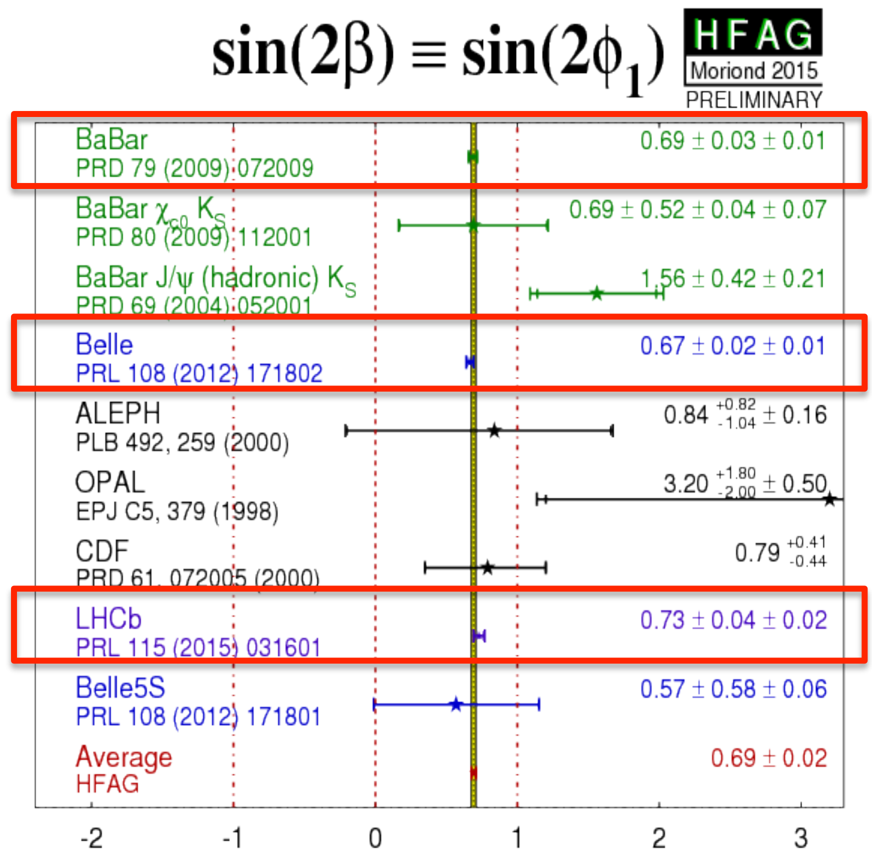
Precision already close to e^+e^- B factories

$$S = +0.731 \pm 0.035(stat) \pm 0.020(syst)$$

$$C = -0.038 \pm 0.032(stat) \pm 0.005(syst)$$

PRL 115, 031601 (2015)

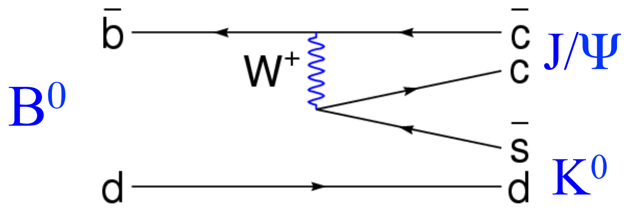




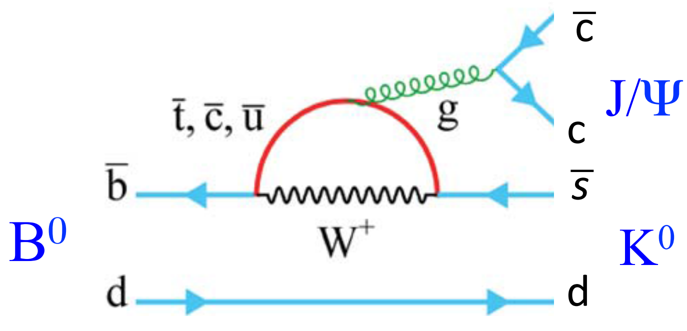
β/ϕ_1 from $b \rightarrow c\bar{u}d$ decays

A closer look to $b \to c\bar{c}s$ transitions

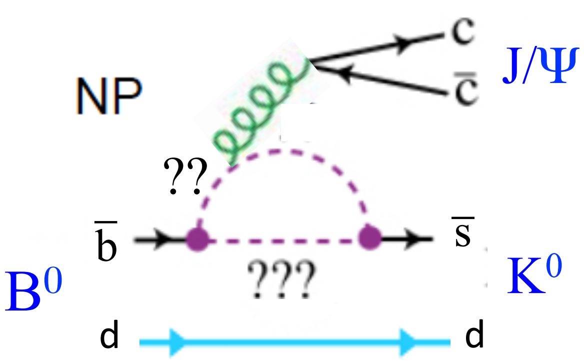
- Precision on sin2β already at ~3%. Expected to go down to less than 1% with next LHC runs and future Belle II data



Leading tree diagram:
No complex phase in decay amplitude

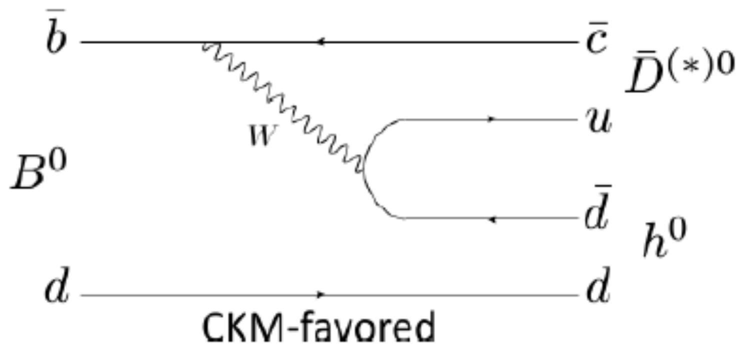


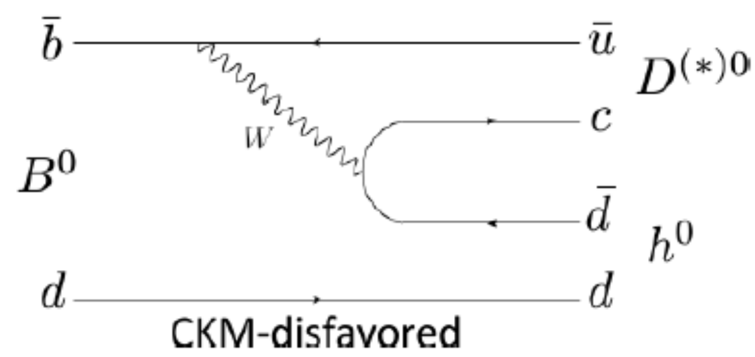
Suppressed SM penguin diagram:
$O(10^{-2})$ effects on sin2β



New Physics penguin diagram

Set a SM reference from $b \to c\bar{u}d$ decays





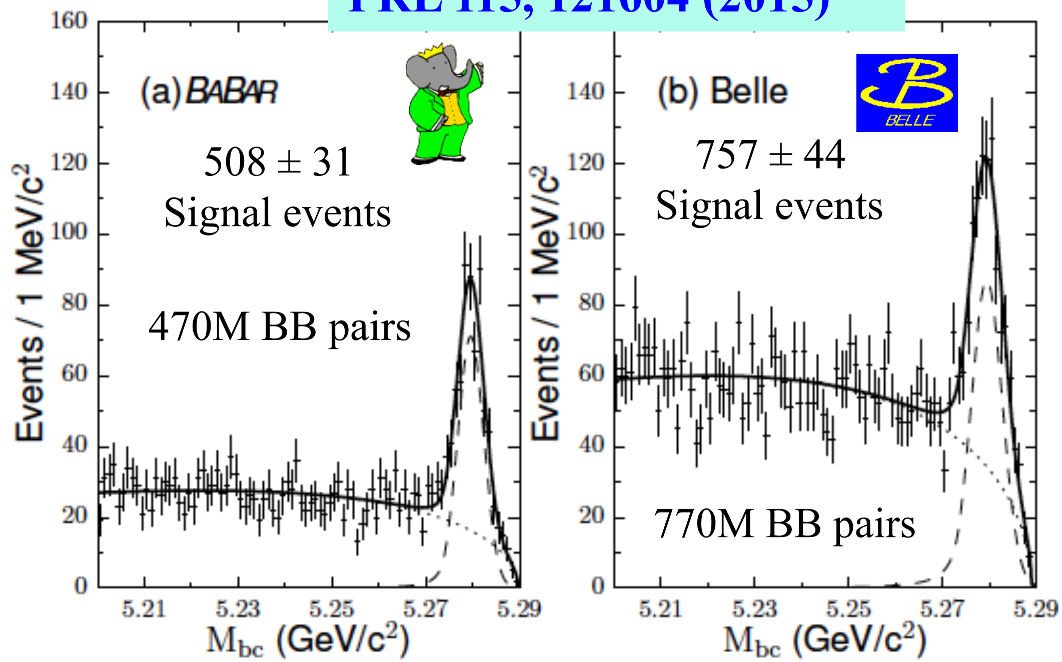
- $B^0 \to D_{CP}{}^{(*)} h^0$ ($h^0 = \pi^0,\eta,\omega$) decays are mediated only by tree-level amplitudes ==> penguin-pollution free
- Theoretically clean [NPB 659, 321 (2003)]
  - Allows to test the precision measurements in $b \to c\bar{c}s$ decays
  - Can provide a SM reference for sin2β
- Experimental difficulties:
  - Low branching fractions (both for B and D_{CP} decays)
  - Low reconstruction efficiencies and large background
- Previous measurements by *BABAR* and Belle could not establish CPV in $B^0 \to D^{(*)0}h^0$

Perform time-dependent CP analysis combining *BABAR* and Belle data sets
==> extract $S = -\eta_{CP}\sin 2\beta$

Combined BABAR-Belle analysis of $B^0 \to D_{CP}^{(*)} h^0$

- $B^0 \to D_{CP}^{(*)} h^0$ reconstructed modes:
  $D^{*0} \to D_{CP}\pi^0$; $D_{CP} \to K^+K^-$, $K_S\pi^0$, $K_S\omega$
  h^0 modes : $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$,
  $\eta \to \pi^+\pi^-\pi^0$, $\omega \to \pi^+\pi^-\pi^0$

PRL 115, 121604 (2015)



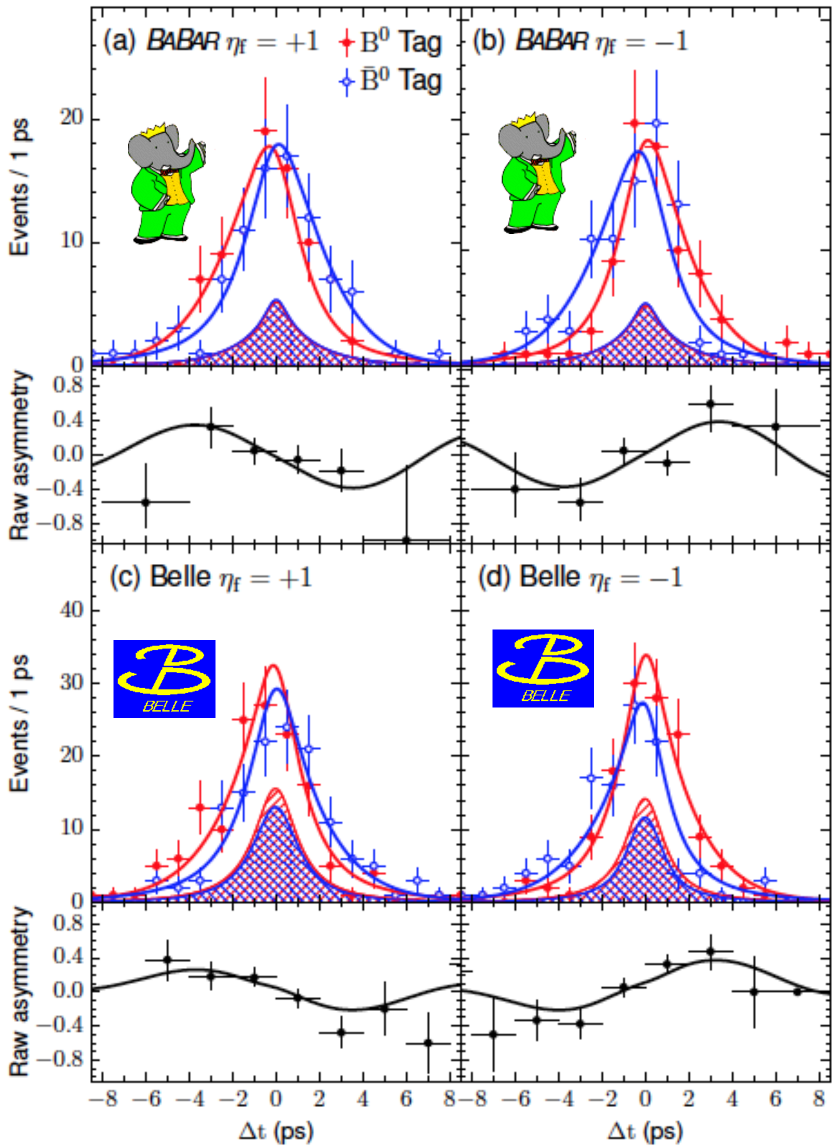
- Apply similar selection on both data sets
- Suppresion of $e^+e^- \to q\bar{q}$ continuum events by a NN algorithm
- Extract signal fraction from reconstructed energy-substituted mass

- Maximize the combined log-likelihood function: $\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{BABAR} + \sum_j \ln \mathcal{P}_j^{\mathrm{Belle}}$
- Apply *BABAR* and Belle specific resolution models and flavor tagging algorithms

- Apply common signal model, to extract CPV parameters

$$P_{\mathrm{sig}}(\Delta t, q) = \frac{1}{4\tau_{B^0}} e^{-\frac{|\Delta t|}{\tau_{B^0}}} \left[1 + q\left(\mathcal{S}\sin(\Delta m \Delta t) - \mathcal{C}\cos(\Delta m \Delta t)\right)\right]$$

Combined BABAR-Belle analysis of $B^0 \to D_{CP}^{(*)} h^0$



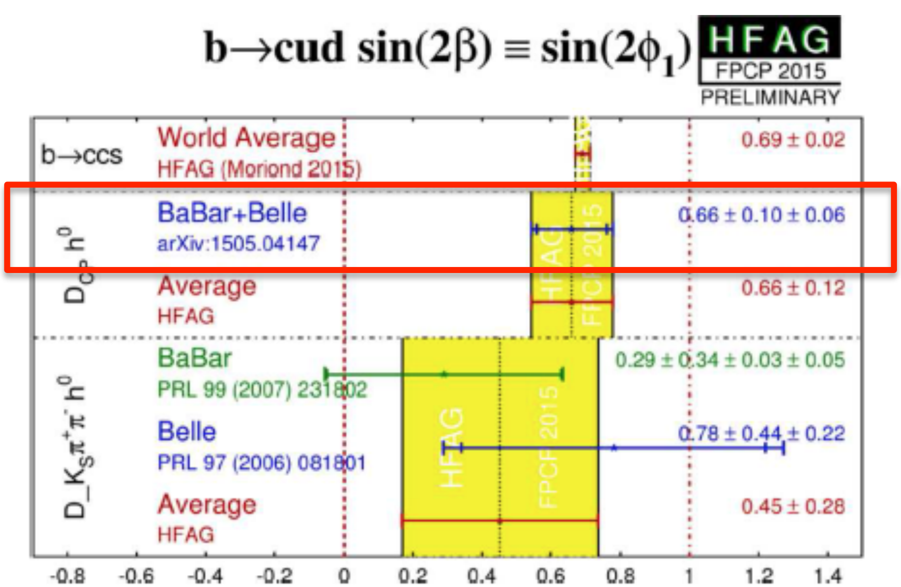
Results of combined analysis (1.1ab^{-1}):

PRL 115, 121604 (2015)

$$-\eta S = +0.66 \pm 0.10(stat) \pm 0.06(syst)$$

$$C = -0.02 \pm 0.07(stat) \pm 0.03(syst)$$

- In agreement with sin2β from $b \to c\bar{c}s$
- First observation of *CPV* in $B^0 \to D_{CP}^{(*)} h^0$ decays (5.4σ)



$B^0 \to D^{(*)0}h^0$, $D^0 \to K_S\pi^+\pi^-$

- Similar to $B^0 \to D_{CP}{}^{(*)0}h^0$, but $D^0 \to K_S\pi^+\pi^-$ is not a *CP* eigenstate
  - Many intermediate states, e.g. $K^{*-}\pi^+$ (favored), $K_S\rho^0$ (CP), $K^{*+}\pi^-$ (DCS)
- The performed analysis combines widely used techniques
  - D^0-decay Dalitz-plot analysis developed for the extraction of angle $\gamma(\phi_3)$
    - Giri *et al.* PRD68, 054018, CLEO-c PRD82, 112008, Belle PRD85, 112014
  - Time-dependent Dalitz-plot analysis to measure β_{eff} in $b \to s$ penguin processes
- The time-dependent analysis can be sensitive to both sin2β and cos2β [Bondar, Gershon, Krokovny, PLB 624, 1 (2005)]

$$P_{\rm sig}(m_+^2, m_-^2, \Delta t) \propto e^{-\frac{|\Delta t|}{\tau_B}}\left[1 + q_B(\mathcal{A}(m_+^2, m_-^2)\cos(\Delta m_B \Delta t) + \mathcal{S}(m_+^2, m_-^2)\sin(\Delta m_B \Delta t))\right]$$

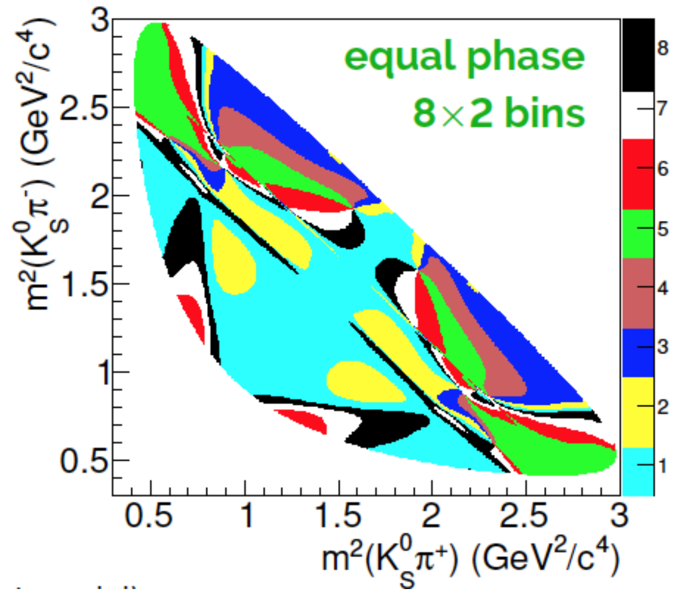
$$\mathcal{S}(m_+^2, m_-^2) \propto {\rm Im}[f(m_-^2, m_+^2) f^*(m_+^2, m_-^2) e^{2\phi_1}]$$

- Model-independent binned analysis of the D^0 Dalitz plot:
  - Define $2\mathcal{N}$ bins symmetric under exchange $m_+^2 \Leftrightarrow m_-^2$
  - Expected number of events in the bin "*i*" of the DP :

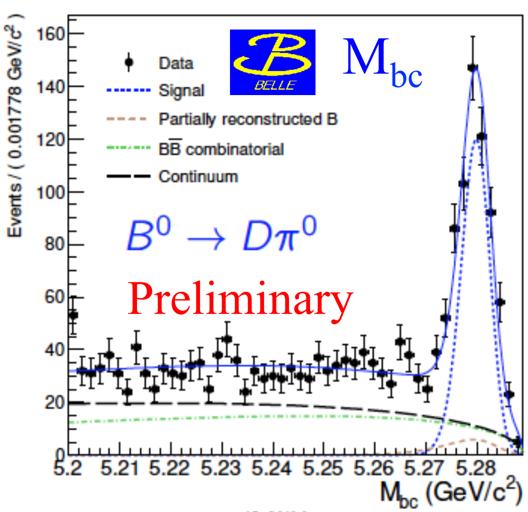
$$N_i(\Delta t, \phi_1) = h_2 e^{-\frac{|\Delta t|}{\tau_B}}\left[1 + Q_B \frac{K_i - K_{-i}}{K_i + K_{-i}}\cos(\Delta m_B \Delta t) + 2Q_B \xi_{h^0}(-1)^l \frac{\sqrt{K_i K_{-i}}}{K_i + K_{-i}}\sin(\Delta m_B \Delta t)(S_i \cos 2\phi_1 + C_i \sin 2\phi_1)\right]$$

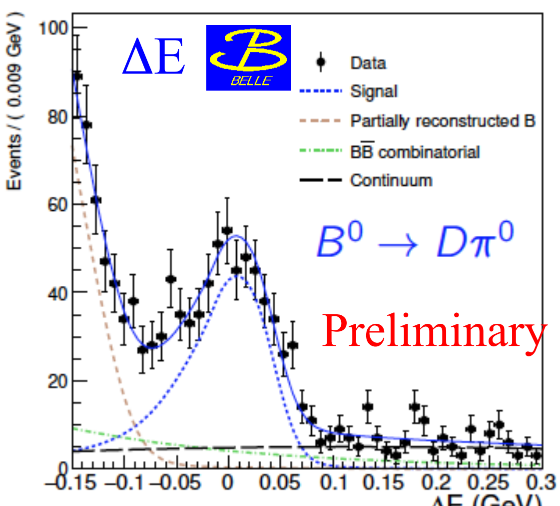
$B^0 \to D^{(*)0}h^0,\, D^0 \to K_S\pi^+\pi^-$

- DP divided in 8x2 *optimized* bins
- Number of events $\mathcal{N}_i$ in each bin parametrized in terms of measured quantities
  - Integrated |amplitude|^2, K_i from $B^- \to D^0\pi^-$
  - S_i and C_i contains info on strong-phase difference between D^0 and $\bar{D}^0$ averaged in the bin "i"
    - from CLEO-c coherent $\psi(3770) \to D^0\bar{D}^0$, with $D^0 \to K_S\pi^+\pi^-$ and $D^0 \to$ CP modes



- $\mathcal{N}_i$ free to float in the fit to M_{bc} and ΔE
- Total signal events: 962 ± 41
- Signal fractions used in the Δt Dalitz fit

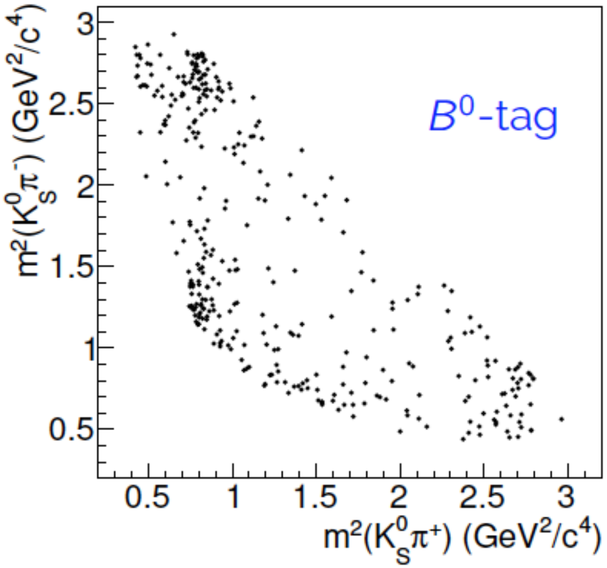


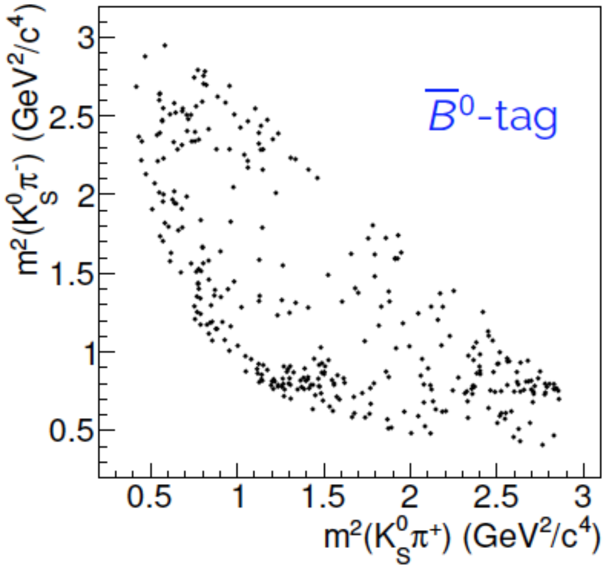


mode	N_{sig}	$f_{sig}(\%)$
$D^0\pi^0$	464 ± 26	72 ± 4
$D^0\eta_{\gamma\gamma}$	99 ± 14	51 ± 7
$D^0\eta_{\pi^+\pi^-\pi^0}$	51 ± 9	66 ± 11
$D^0\omega$	182 ± 18	58 ± 6
$D^0\eta'$	28 ± 6	70 ± 16
$D^{*0}\pi^0$	103 ± 17	44 ± 7
$D^{*0}\eta$	36 ± 8	64 ± 13

$B^0 \to D^{(*)0}h^0$, $D^0 \to K_S\pi^+\pi^-$

Flavor-tagged Dalitz plot





Clear pattern visible for B^0-tagged and $\overline{B}^0$-tagged Dalitz plots
(sample of events selected with good tag probability)

Results of the TD fit:

Preliminary

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

Preliminary

$$\beta = \phi_1 = (11.7 \pm 7.8 \pm 2.1)^o$$

Disfavor the second solution from $b \to c\bar{c}s$ golden modes

$\phi_1 = 21.9°$ (1.3σ away)

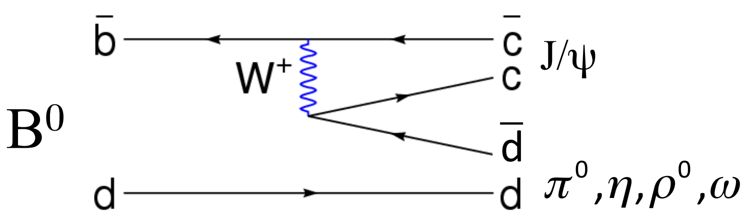
$\phi_1 = 68.1°$ **(5.1σ away)**

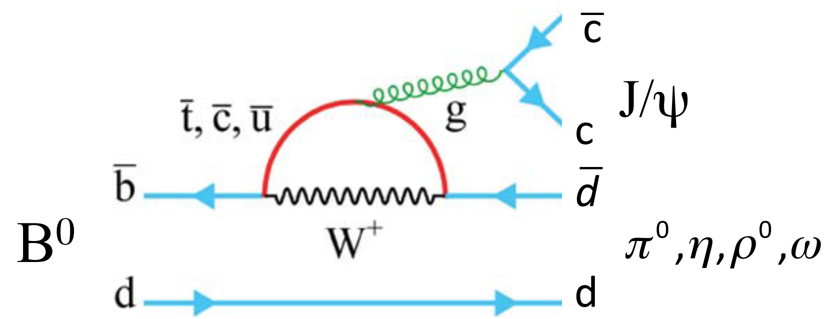
β/ϕ_1 : Constraints from $b \to c\bar{c}d$ decays

Constraining the effect of penguin pollution in $b \to c\bar{c}s$

- Penguin diagrams in $b \to c\bar{c}s$ with different weak phase are doubly Cabibbo-suppressed
- Penguin diagrams in $b \to c\bar{c}d$ are of the same order as the tree diagram

$\Rightarrow$ Use $2\beta_{eff} = 2\beta + \Delta 2\beta$ measured in these decays, together with SU(3) symmetry, to constrain size and phase shift due to penguin pollution in favored $b \to c\bar{c}s$: $\delta_p \sim \varepsilon \Delta 2\beta$, where $\varepsilon = \lambda^2/(1-\lambda^2) \sim 0.053$, is the *P/T* Cabibbo-suppression factor





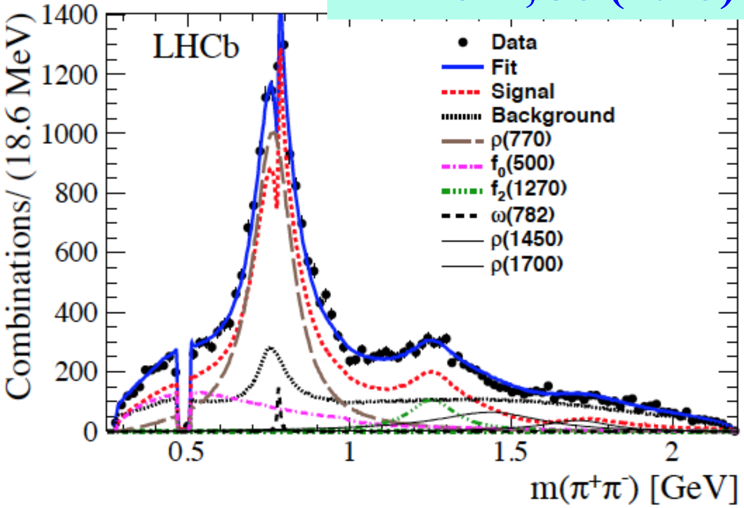
Examples:

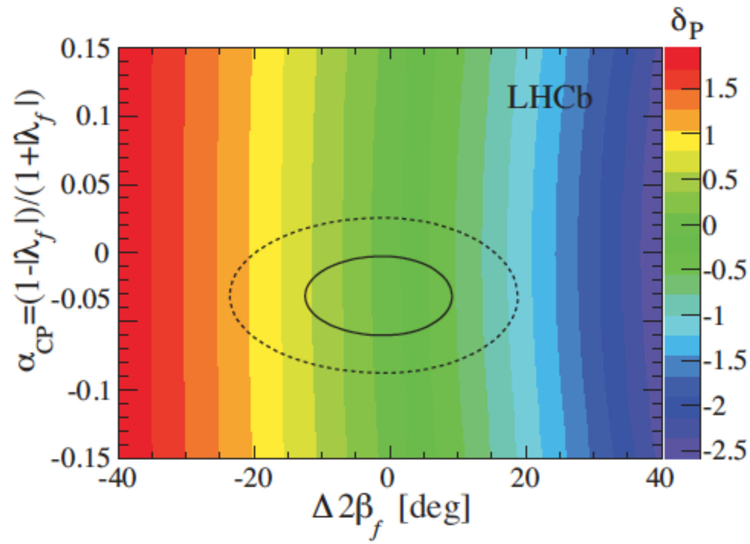
- $B_d \to J/\psi\, \pi^0$, $J/\psi\, \rho^0$ to constrain $\Delta 2\beta \equiv \Delta\phi_d$ in $B_d \to J/\psi\, K^0$ [Ciuchini *et al.*, PRL 95, 221804; Faller *et al.*, PRD 79, 014030]
- $B_d \to J/\psi\, \pi^+\pi^-$ and $B_s \to J/\psi\, K^{*0}$ to constrain $\Delta\phi_s$ in $B_s \to J/\psi\, \phi$ [Faller *et al.*, PRD 79, 014005]
- Similar arguments hold for other charmonium states

$B^0 \rightarrow J/\psi\, \pi^+\pi^-$

- $J/\psi\, \rho^0$ accounts for about 65% of $B^0 \rightarrow J/\psi\, \pi^+\pi^-$ decays.
- Longitudinal polarization (*CP*-even) has largest fraction (*CP*-odd component~20%)

PLB 742, 38 (2015)





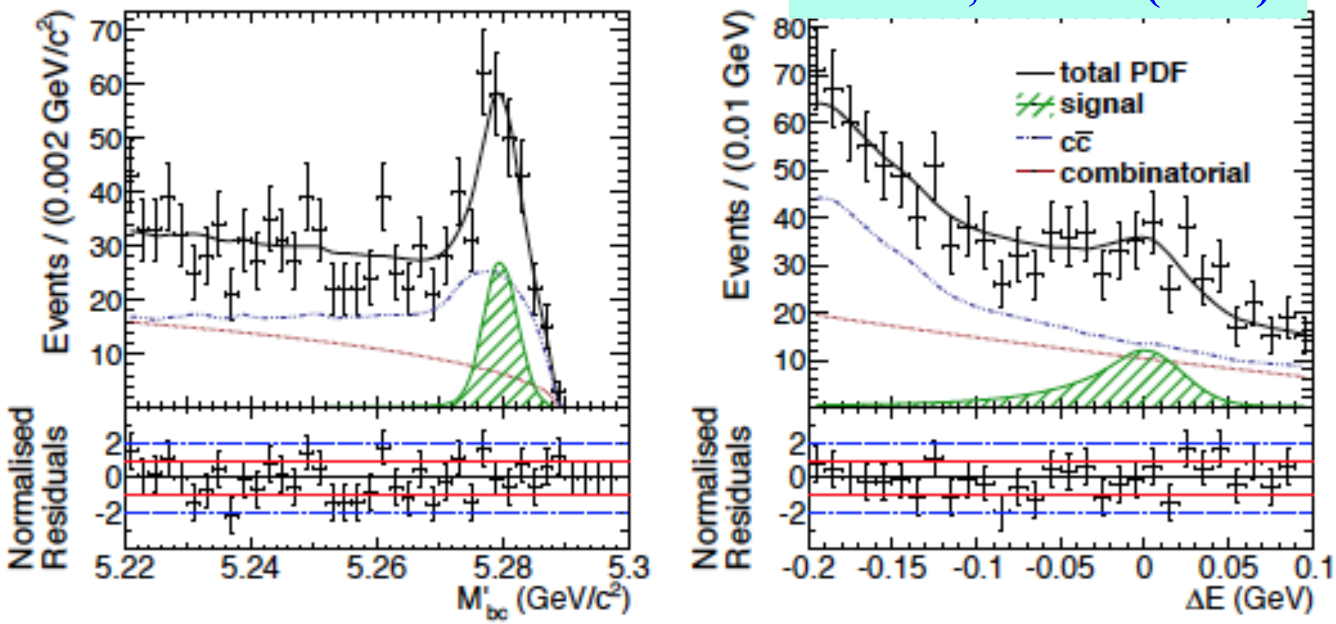
- Measured from TD analysis of this decay: $2\beta_{eff} \equiv 2\phi_1^{eff} = (41.7\ \pm 9.6^{+2.8}_{-6.3})^o$ $\Longrightarrow \Delta 2\beta = 2\beta_{eff} - 2\beta = (-0.9 \pm 9.7^{+2.8}_{-6.3})^o$
- The large error on $\Delta 2\beta$ limits the constraint on δ_p to about $\pm 1^o$

- Analogous constraints from $B_d \rightarrow J/\psi\, \pi^0$ measured at *BABAR* and Belle [Ciuchini *et al.*, PRL 95, 221804]

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

- By the same arguments $B^0 \to \psi(2S)\,\pi^0$ decays can be used to constrain the penguin contamination in $B^0 \to \psi(2S)\,K^0$ decays
- Recent observation of this decay at Belle

PRD 93, 031101 (2016)



85 ± 12
signal events

$\mathcal{B}(B^0 \to \psi(2S)\,\pi^0) = (1.17 \pm 0.17(\mathrm{stat}) \pm 0.08(\mathrm{syst}))\ \mathrm{x}10^{-5}$

Statistical significance of 7.2σ from a scan of the likelihood function

Time-dependent analysis of this decay with high statistics can provide useful constraints. Difficult at LHCb. Good perspectives for Belle II

α/ϕ_2

Constraints on $\alpha \equiv \phi_2$ [from EPS 2015]

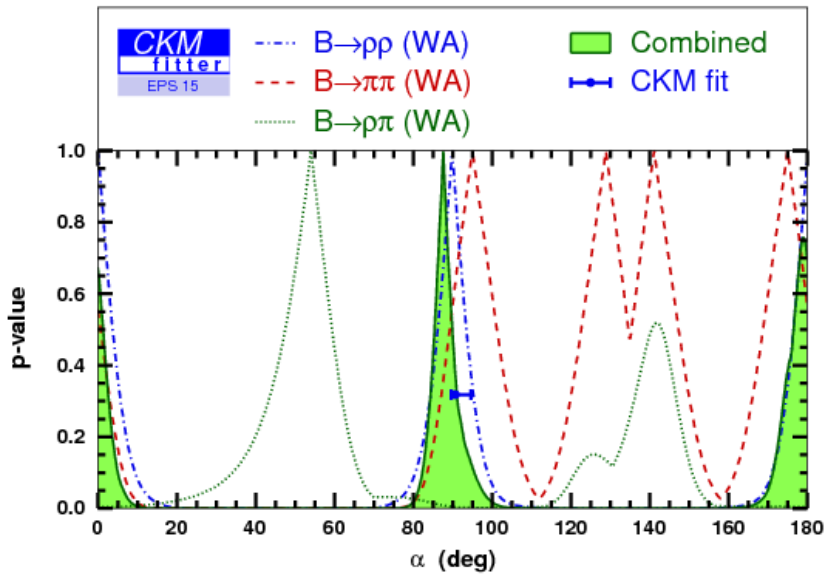
$\alpha = \varphi_2$ accessible via $b \to u$ transitions in $B \to \pi\pi, B \to \rho\rho$, or $B \to \rho\pi$

- Measure time-dependent *CP* asymmetries as for sin2β
- Sizable penguin contribution with different weak phase

Expect:

$C \neq 0$ allowed

$$S = \sqrt{1-C^2}\,\sin 2\alpha_{eff} = \sin(2\alpha + 2\Delta\alpha)$$



$$\alpha[\pi\pi] = \left(95.0^{+8.8}_{-7.9}\right)^\circ$$

$$\alpha[\rho\rho] = \left(89.9^{+5.4}_{-5.5}\right)^\circ$$

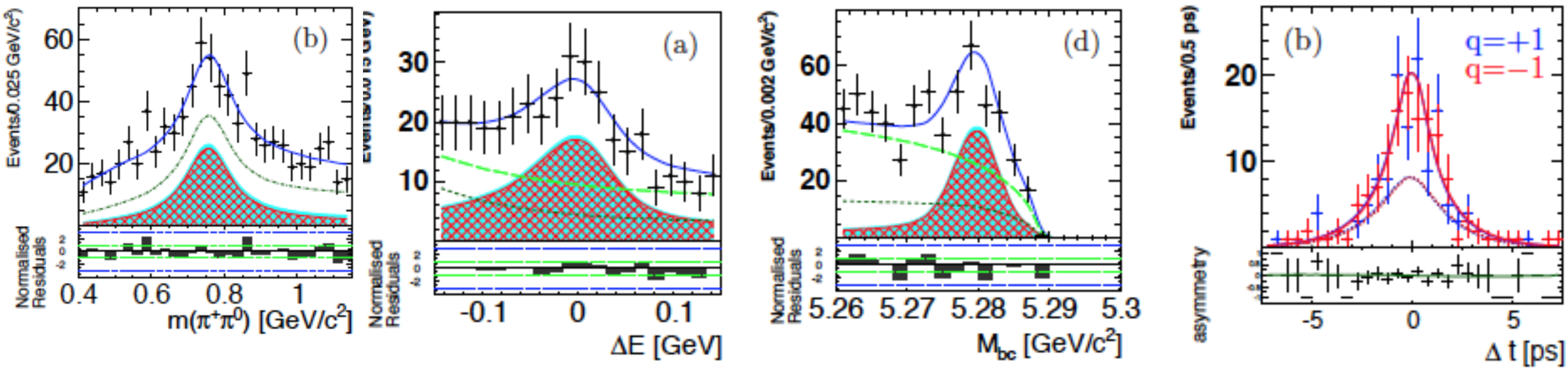
$$\alpha[all] = \left(87.6^{+3.5}_{-3.3}\right)^\circ$$

- Consistent with the prediction from the global CKM fit (not including the α-related measurements): $\alpha[fit] = \left(90.6^{+3.9}_{-1.1}\right)^\circ$
- Good consistency also between fit with *BABAR*-only and Belle-only measurements

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

PRD 93, 032010 (2016)

- Use full statistics to measure simultaneously with a Time-Dependent analysis:
  - BF, f_L, CPV parameters (A_{CP}, S_{CP})
- The $\rho^+\rho^-$ V-V state is a superposition of three helicity amplitudes, dominated by A_0: CP-even state, with $\rho^\pm$ mesons longitudinally polarized
  - Angular analysis to disentangle the various components



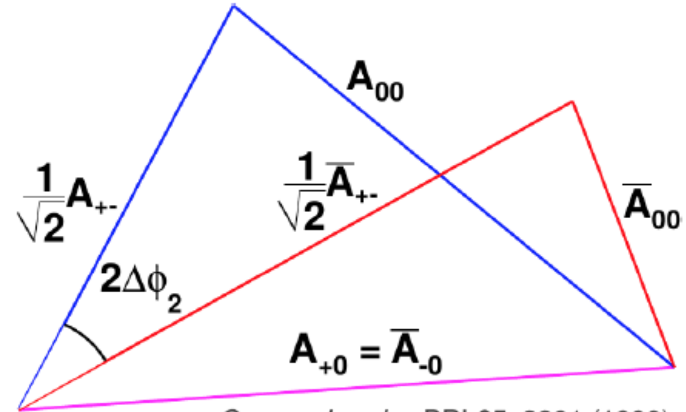
- Consistent with previous results (superseding old Belle measurements)

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

$B^0 \to \rho^+\rho^-$: constraints on α (1)

Method A: Isospin relations

$$\frac{1}{\sqrt{2}}A_{+-} + A_{00} = A_{+0}, \qquad \frac{1}{\sqrt{2}}\bar{A}_{+-} + \bar{A}_{00} = \bar{A}_{-0}$$



Gronau, London PRL**65**, 3381 (1990)

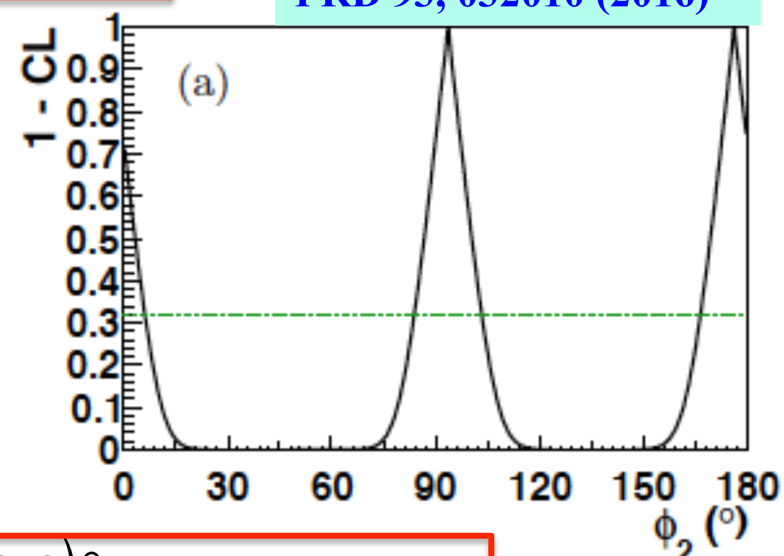
Need to determine $2\Delta\phi_2$ to extract the true value of $2\phi_2$, from the measured CP asymmetry $S_{\rho+\rho-}$

$$\boxed{C_{\rho\rho} \neq 0; \quad S_{\rho\rho} = \sqrt{1-C^2}\sin 2\phi_2^{eff} \qquad \phi_2^{eff} = \phi_2 + \Delta\phi_2}$$

Use experimental inputs from Belle measurements, and perform a probability scan on $\alpha=\phi_2$:

- $\rho^+\rho^-$: **Br, A_{CP}, f_L** This work
- $\rho^+\rho^0$: **Br, f_L** PRL 91, 221801
- $\rho^0\rho^0$: **Br, A_{CP}, f_L** PRD 89, 072008

PRD 93, 032010 (2016)



SM favored value: $\phi_2 = (93.7 \pm 10.6)^\circ$
Penguin pollution almost negligible: $\Delta\phi_2 = (0.0 \pm 9.6)^\circ$

$B^0 \to \rho^+\rho^-$: constraints on α (2)

(Alternative) method B: SU(3) symmetry

The decay amplitude is written in terms of the tree (T) and penguin (P) contribution:

$$\mathcal{A}_{B^0\to\rho^+\rho^-} = Te^{i\phi_3} + Pe^{i\delta_{PT}}$$

$B^0\to \rho^+\rho^-$ is related via SU(3) to the pure penguin mode $B^0\to K^{0*}\rho^+$ [use Belle results PRL95, 141801 (2005)]

$$\frac{\mathcal{B}_{\rm LP}(B^+\to K^{*0}\rho^+)}{\mathcal{B}_{\rm LP}(B^0\to\rho^+\rho^-)} = \frac{\tau_{B^\pm}}{\tau_{B^0}}\left(\frac{|V_{cs}|f_{K^*}}{|V_{cd}|f_\rho}\right)^2 \frac{Fr^2_{PT}}{1-2r_{PT}\cos\delta_{PT}\cos(\phi_1+\phi_2)+r^2_{PT}}$$

Use experimental inputs from $b\to c\bar{c}s$ and from $B^0\to K^{0*}\rho^+$, to perform a probability scan on $\alpha=\phi_2$

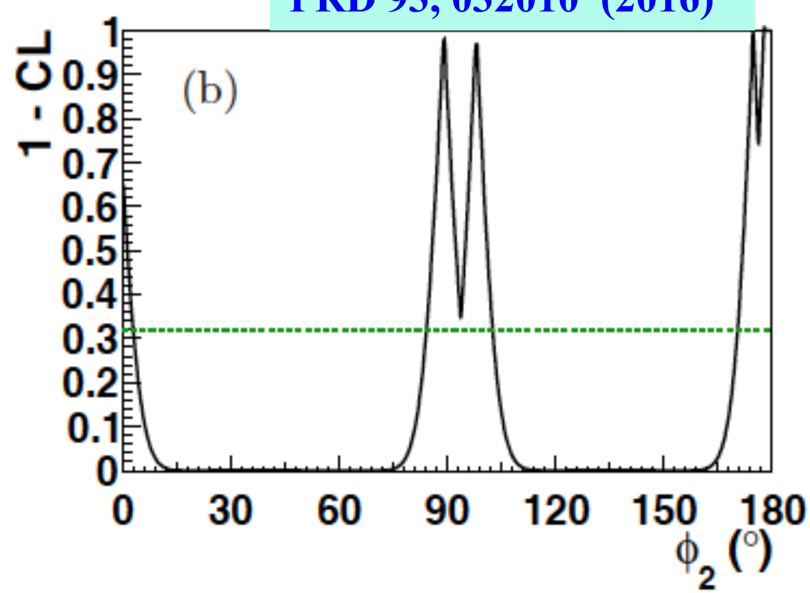
SM favored value (with $\delta_{PT}<90^o$):

$$\phi_2 = (89.3 \pm 4.8\ (\mathrm{scan})^{+1.0}_{-3.4}\ (\mathrm{SU(3)}))^\circ$$

$$r_{PT} = 0.09 \pm 0.02\ (\mathrm{scan})^{+0.06}_{-0.02}\ (\mathrm{SU(3)})$$

$$\delta_{PT} = (0.0 \pm 48.7\ (\mathrm{scan}) \pm 0.0\ (\mathrm{SU(3)}))^\circ$$

PRD 93, 032010 (2016)



About $B^0 \to \rho^0\rho^0$

- *BABAR* and Belle measurements of f_L show a difference at ~2σ level

BABAR: $\mathcal{B} = (0.92 \pm 0.32 \pm 0.14) \times 10^{-6}$ PRD 78, 071104(R) (2008)

$f_L = 0.75^{+0.11}_{-0.14} \pm 0.05$

BELLE: $\mathcal{B} = (1.02 \pm 0.30 \pm 0.15) \times 10^{-6}$ PRD 89, 072008 (2014)

$f_L = 0.21^{+0.18}_{-0.22} \pm 0.15$

- Thus, the extraction of α with the isospin relations could be different if world average values are used for the various parameters, instead of Belle-only results
- Needs more data to clarify this issue.
- Recent LHCb measurement based on the full 3.1fb^{-1} data set
  - First observation (at >7σ) of the branching braction
  - Result on f_L closer to *BABAR* one

PLB 747, 468 (2015)

LHCb

$\mathcal{B}(B^0 \to \rho^0\rho^0) = (0.94 \pm 0.17 \pm 0.09 \pm 0.06^{*}) \times 10^{-6}$ **(7.1σ)**

$f_L(B^0 \to \rho^0\rho^0) = 0.745^{+0.048}_{-0.058} \pm 0.034$ (First observation)

Conclusions

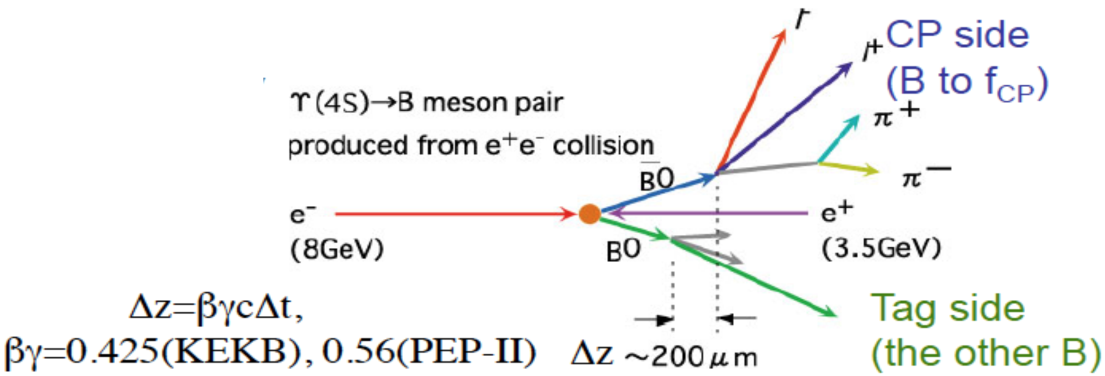
- Precision on sin2β from $b \to c\bar{c}s$ decays reached about 3% (σ(β) ~0.7° [HFAG15])
- LHCb Run1 ($3fb^{-1}$) already very competive on $B^0 \to J/\psi K_S$
- Good prospects for LHCb Run2, and in longer term for both LHC and Belle II
  - Strong constraints on SM penguin pollution will be essential
  - Presented today recent investigations of $b \to c\bar{u}d$ and $b \to c\bar{c}d$ decays

- Constraints on α also becoming stringent (σ(α) <4° from CKMfitter)
  - Extraction from isospin relations or SU(3) symmetry arguments
  - Precise measurements of branching fractions and TD asymmetries needed
  - Projections at Belle II for an error on α of ~1°

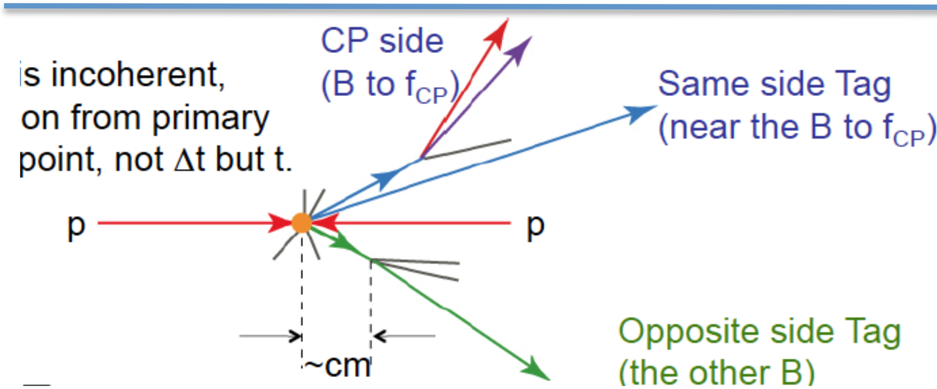
- The ~1.5 ab^{-1} of data collected by *BABAR* and Belle proven to be still very effective, because of the complementarity with LHCb.
  - These data should be exploited as much as possible until Belle II becomes fully operational

BACKUP
slides

Experimental methods



- Coherent B0-B0bar production
- Asymmetries depend on Δt
- Use precise kinematical information from beam-spot and two B vertices. ΔE and M_{ES} (M_{BC})
- Event shape variables to reject jet-like $e^+e^- \rightarrow qqbar$ events



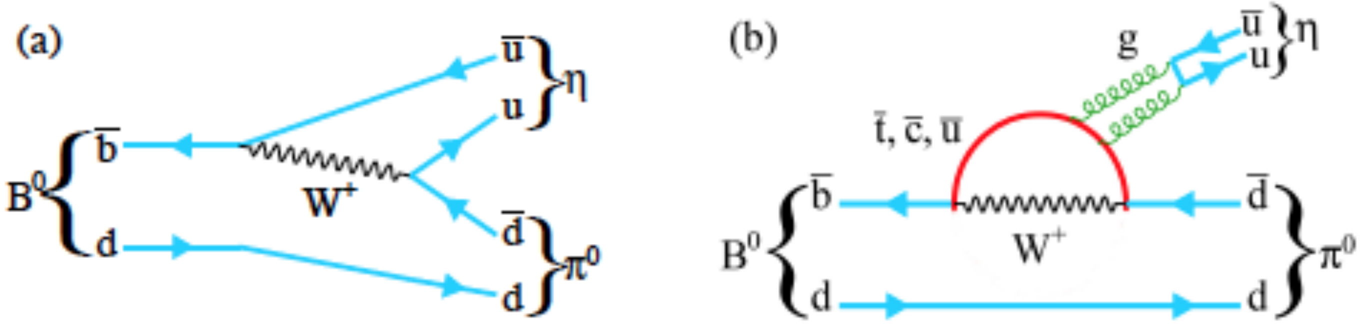
- Oscillation is incoherent
- Time evolution from production point
- Asymmetries depend on t
- Much higher production rate
- Lower tagging efficiency
- Better time resolution due to larger boost

	Number of usable B_d	Flavor tagging	Δt or t resolution	Oscillation
Υ(4S), i.e. BaBar, Belle/Belle II	1 million/fb^{-1}	$\varepsilon(1-2w)^2$ =30%	500~600 fs (~1/3×τ_B)	Coherent oscillation
LHCb	1000~2000 million/fb^{-1}	$\varepsilon(1-2w)^2$ =3%	50~60 fs	Incoherent oscillation

PRD **92**, 011101 (2015)

$B^0 \to \eta\pi^0$

- Same diagrams as $B \to \pi^0\pi^0$

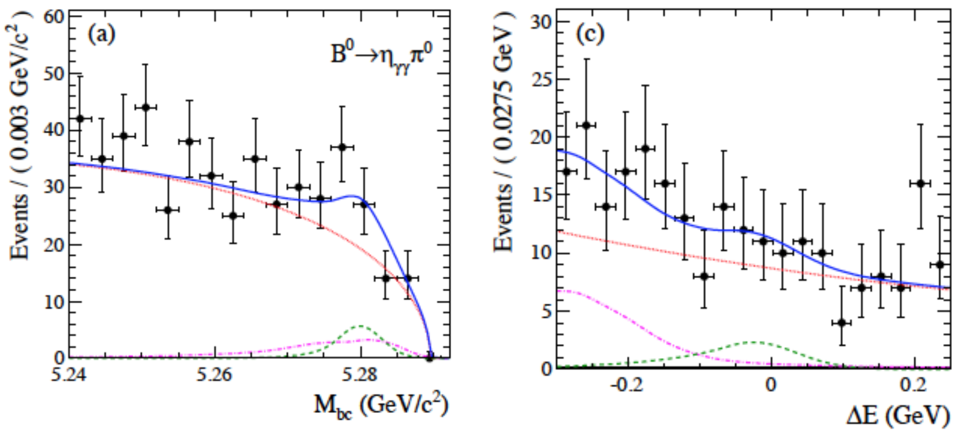


- The Branching Fractions can be used to constrain isospin-breaking effects on the value of sin2α measured in $B \to \pi\pi$ decays
  [Gronau et al, PRD71, 074017 (2005); Gardner, PRD72 034015 (2005)]
- But also to constrain *CPV* parameters ($C_{\eta' K}$, $S_{\eta' K}$) of $B \to \eta' K$
  [Gronau et al, PLB596, 107 (2004); Gronau et al, PRD74, 093003 (2006)]

- Theory expectations: $\mathcal{B}(B^0 \to \eta\pi^0) \sim (2\text{–}12)\text{x}10^{-7}$
- Previous measurements:
  - Belle $\mathcal{B} < 2.5 \times 10^{-6}$ [PRD 71, 091106 (2005)]
  - *BABAR* $\mathcal{B} < 1.5 \times 10^{-6}$ [PRD 78, 011107 (2008)]

$B^0 \rightarrow \eta\pi^0$

- New measurement from Belle based on 753 10^6 BB pairs
- η's reconstructed in $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow \pi^+\pi^-\pi^0$
- Large background from e+e- $\rightarrow$ qqbar processes
  - Suppressed with a multivariate analyzer based on a Neural Network
  - Signal extracted from a simultaneous unbinned ML fit to Mbc, DE and the NN variable



Mode	$Y_{\rm sig}$	$\epsilon(\%)$	$\mathcal{B}_\eta(\%)$	Significance	$\mathcal{B}(10^{-7})$
$B^0 \to \eta_{\gamma\gamma}\pi^0$	$30.6^{+12.2}_{-10.8}$	18.4	39.41	3.1	$5.6^{+2.2}_{-2.0}$
$B^0 \to \eta_{3\pi}\pi^0$	$0.5^{+6.6}_{-5.4}$	14.2	22.92	0.1	$0.2^{+2.8}_{-2.3}$
Combined				3.0	$4.1^{+1.7}_{-1.5}$

- Combined Branching Fraction (first evidence of the decay mode):

$$\mathcal{B}\left(B^0 \to \eta\pi^0\right) = \left(4.1^{+1.7\,+0.5}_{-1.5\,-0.7}\right)\times 10^{-7}$$ ($\mathcal{B} < 6.5 \times 10^{-7}$ @90%C.L.)

PRD **92**, 011101 (2015)

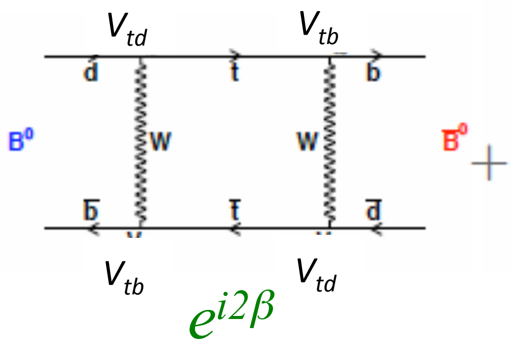
- Within the range predicted by theory.
- Using this value in [PRD71,074017] the isospin-breaking corrections to the value of α measured in B $\rightarrow \pi\pi$ decays due to mixing result <0.97° at 90%C.L.

The angle $\alpha \equiv \phi_2$

$\alpha = \varphi_2$ accessible via $b \to u$ transitions in $B \to \pi\pi, B \to \rho\rho$, or $B \to \rho\pi$

Measure Time-dependent CP asymmetries as for sin2β

e.g. $B \to \pi^+\pi^-$ and $B \to \overline{B} \to \pi^+\pi^-$ interference



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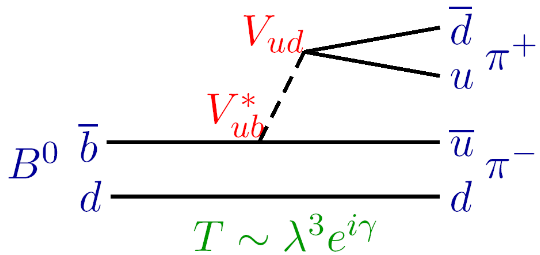
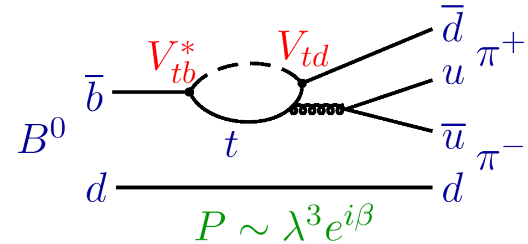


Sizable penguin contribution with different weak phase



At tree level

$C = 0$

$S = \sin 2\alpha$

Because of penguin pollution

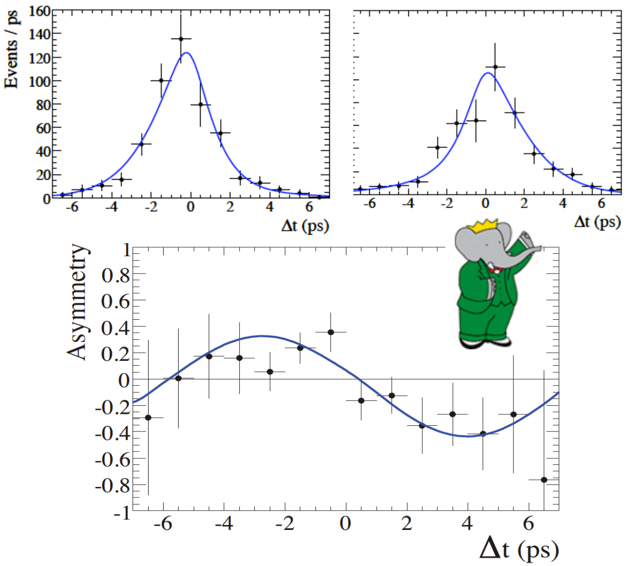
$C \neq 0$ allowed

$S = \sqrt{1 - C^2} \sin 2\alpha_{eff} = \sin(2\alpha + 2\Delta\alpha)$

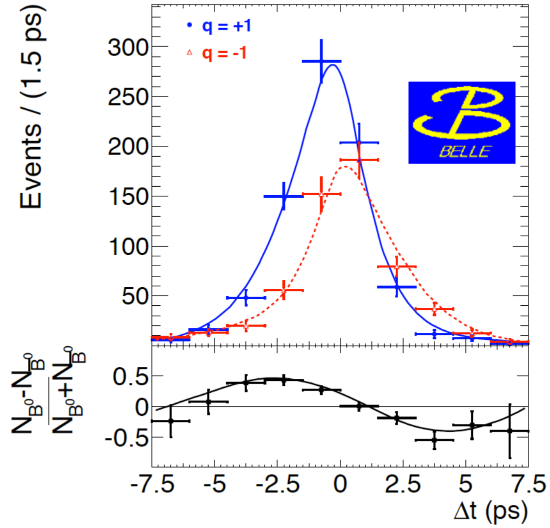
Needs measurement of $B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^0\pi^0$ processes and isospin analysis to recover sin2α

$B \to \pi^+\pi^-$: present status

PRD **87**, 052009 (2013)



PRD **88**, 092003 (2013)



JHEP **1310**, 183 (2013)