CPV in the SM

- Three discrete operations are potential symmetries of a field theory Lagrangian:
  - Parity, P: (t, x) → (t, -x)
  - Time reversal, T: (t, x) → (-t, x)
  - Charge conjugation, C: particle → antiparticle

- CP replaces particle by its antiparticle and reverses momentum and helicity
- CPT is an exact symmetry in any local Lagrangian field theory

- Standard Model Lagrangian is hermitian and Lorentz invariant and is defined in terms of scalar operators O_i:

$$\mathcal{L}(x) = \sum_i \left(a_i \mathcal{O}_i(x) + a_i^* \mathcal{O}_i^\dagger(x) \right)$$

- O_i depend on terms bilinear in fermion fields

- The transformation rules of the bilinear fermion terms, of the scalar (H), pseudoscalar (A) and vector boson (W) fields, and of the derivative operator, imply each combination of fields and derivatives in the Lagrangian transforms under CP to its hermitian conjugate.

CPV in the SM

- Coefficients a_i are coupling constants or particle masses which not transform under CP.

$$\mathcal{L}(x) = \sum_i \left(a_i \mathcal{O}_i(x) + a_i^* \mathcal{O}_i^\dagger(x) \right)$$

- If any of these quantities are complex, CP is not necessarily a good symmetry of the Lagrangian, reflecting in rate differences between pairs of CP conjugate processes.

- Not all the phases are physically meaningful.
- Any field can be redefined by an arbitrary phase rotation that will not change the physics.

  - Some sets of couplings can be made real by these redefinitions. If any non-zero phase for couplings remains there is CP violation.

- CP is broken in any theory that has complex coupling constants in the Lagrangian which cannot be removed by any choice of phase redefinition of the fields in the theory

CPV in CKM Matrix

- In the SM there are in principle two sources of CPV:
  - Strong CPV: originates from special features of the QCD vacuum which would impact the neutron electric dipole moment (EDM).
  - Current limit $d_N < 0.29 \times 10^{-25}$ e cm strongly constrains this CPV source

    [Kim, Carosi, Rev. Mod. Phys. 82, 557-602 (2010)]

  - CKM Matrix
- All terms in the SM Langrangian are CP invariant except for the charged current interaction term

$$H_{cc} = \frac{g}{\sqrt{2}} \left(\overline{u}_L \, \overline{c}_L \, \overline{t}_L\right) V_{\rm CKM} \gamma^\mu \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W^+_\mu.$$

transforming as:

$$\left(\overline{u}_L \, \overline{c}_L \, \overline{t}_L\right) V_{\rm CKM} \gamma^\mu \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} W^+_\mu \xrightarrow{CP} \left(\overline{d}_L \, \overline{s}_L \, \overline{b}_L\right) V^T_{\rm CKM} \gamma^\mu \begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix} W^-_\mu$$

- The combination $H_{cc} + H^{\dagger}_{cc}$ appearing in the Langrangian is:

$$g V_{ij} \overline{u}_i \gamma_\mu W^{+\mu} (1 - \gamma_5) d_j + g V^*_{ij} \overline{d}_j \gamma_\mu W^{-\mu} (1 - \gamma_5) u_i$$

- CP operation interchanges the two terms except that V_{ij} and V^*_{ij} are not interchanged.
- CKM parameters are complex and is not possible to find a mass basis and choice of phase convention where all couplings and masses are real → CPV

CPV in CKM Matrix

Formalism

- Flavor eigenstates M and $\overline{M}$ and final states f and $\overline{f}$ are related through CP transformations ($CP^2 = 1$):

$$CP|M\rangle = e^{+i\xi_M}\,|\overline{M}\rangle\ , \quad CP|f\rangle = e^{+i\xi_f}\,|\overline{f}\rangle$$

$$CP|\overline{M}\rangle = e^{-i\xi_M}\,|M\rangle\ , \quad CP|\overline{f}\rangle = e^{-i\xi_f}\,|f\rangle$$

where the phases are arbitrary and unobservable as the states are defined through strong interactions only (CP conserving)

- Decay amplitudes:

$$A_f = \langle f\,|\mathcal{H}|\,M\rangle\ , \quad \overline{A}_f = \langle f\,|\mathcal{H}|\,\overline{M}\rangle$$

$$A_{\overline{f}} = \langle \overline{f}\,|\mathcal{H}|\,M\rangle\ , \quad \overline{A}_{\overline{f}} = \langle \overline{f}\,|\mathcal{H}|\,\overline{M}\rangle$$

which depend on weak interaction, are sensitive to the arbitrary phase definition

- If CP is conserved, [CP, H] = 0 and the amplitudes of CP conjugate processes have the same magnitude and an arbitrary unphysical relative phase:

$$\overline{A}_{\overline{f}} = e^{i(\xi_f - \xi_M)}\,A_f$$

CPV in the B sector

Possible manifestation of CPV can be classified in a model-independent way:

- CPV in decay (direct): the amplitude for a decay and its CP conjugate process have different magnitudes:

$$|\overline{A}_{\overline{f}}/A_f| \neq 1$$

  - Only possible CPV in charged meson (and all baryon) decays (no mixing)

$$\mathcal{A}_{f^\pm} \equiv \frac{\Gamma(M^- \to f^-) - \Gamma(M^+ \to f^+)}{\Gamma(M^- \to f^-) + \Gamma(M^+ \to f^+)} = \frac{|\overline{A}_{f^-}/A_{f^+}|^2 - 1}{|\overline{A}_{f^-}/A_{f^+}|^2 + 1} \qquad (1)$$

- CPV in mixing: the two neutral mass eigenstates are not CP eigenstates (already discussed):

$$|B_{\mathrm{L,H}}\rangle = p|B_q^0\rangle \pm q|\overline{B}_q^0\rangle \qquad |q/p| \neq 1$$

  - Only possible CPV in neutral meson inclusive semileptonic decays $\overline{B}^0$, $B^0 \to l^\pm X$ because $|A_{\ell^+X}| = |\overline{A}_{\ell^-X}|$ and (direct) $A_{\ell^-X} = \overline{A}_{\ell^+X} = 0$.

$$\mathcal{A}_{\mathrm{SL}}(t) \equiv \frac{d\Gamma/dt\left[\overline{M}^0_{\mathrm{phys}}(t) \to \ell^+X\right] - d\Gamma/dt\left[M^0_{\mathrm{phys}}(t) \to \ell^-X\right]}{d\Gamma/dt\left[\overline{M}^0_{\mathrm{phys}}(t) \to \ell^+X\right] + d\Gamma/dt\left[M^0_{\mathrm{phys}}(t) \to \ell^-X\right]} = \frac{1-|q/p|^4}{1+|q/p|^4}. \qquad (2)$$

CPV in the B sector

- CPV in interference between decays with and without mixing:

- Neutral B decays into final CP eigenstates common to B^0 and $\overline{B}^0$:
  $B^0 \rightarrow f$, $B^0 \rightarrow \overline{B}^0 \rightarrow f$
- Quantity of interest independent on phase conventions:

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

- CP is conserved if: $|q/p| = 1$, $|\bar{A}_{f_{CP}}/A_{f_{CP}}| = 1$ and no relative phase:

$$\lambda_f \neq \pm 1 \rightarrow CP\ Violation$$

- This CPV can be observed in time-dependent asymmetries of neutral M meson decays into final CP eigenstates f_{CP}

$$\mathcal{A}_{f_{CP}}(t) \equiv \frac{d\Gamma/dt\left[\overline{M}^0_{\rm phys}(t) \rightarrow f_{CP}\right] - d\Gamma/dt\left[M^0_{\rm phys}(t) \rightarrow f_{CP}\right]}{d\Gamma/dt\left[\overline{M}^0_{\rm phys}(t) \rightarrow f_{CP}\right] + d\Gamma/dt\left[M^0_{\rm phys}(t) \rightarrow f_{CP}\right]} \quad (3)$$

CPV in the B sector

- CPV in interference between decays with and without mixing:

- Neutral B decays into final CP eigenstates common to B^0 and $\overline{B}^0$:
  $B^0 \to f$, $B^0 \to \overline{B}^0 \to f$
- Quantity of interest independent on phase conventions:

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

- CP is conserved if: $|q/p| = 1, \ |\bar{A}_{f_{CP}} / A_{f_{CP}}| = 1$ and no relative phase:

$$\lambda_f \neq \pm 1 \rightarrow CP\ Violation$$

- This CPV often occurs in combination with the other two types

- If $|\lambda_f| = 1, \ \Im\lambda_f \neq 0$: No CPV in mixing and No CPV in decay

  - In this case CPV in the interference between mixing and decay is the only source of CP asymmetry

CPV in the B sector

- CP conjugate amplitudes B → f and $\overline{B}$ → $\overline{f}$ include two types of phases:
  - Phases of complex parameters in the couplings of the W boson appear with opposite signs in the CP conjugate amplitudes: Weak Phases. The weak phase of each term is convention-dependent, the physics is in the difference between pairs of phases
  - Intermediate on-shell states in the decay generated by CP-invariant strong interactions give phases with the same sign in the CP-conjugate amplitudes: Strong Phases.
- CPV is due to irreducible phases of couplings constants and is observable looking at interference effects. Simplest example is the amplitude of the B → f and the conjugate $\overline{B}$ → $\overline{f}$ processes, consisting of two distinct contributions (1 & 2):

$$A_f = |a_1| e^{i(\delta_1 + \phi_1)} + |a_2| e^{i(\delta_2 + \phi_2)}$$
$$\overline{A}_{\overline{f}} = |a_1| e^{i(\delta_1 - \phi_1)} + |a_2| e^{i(\delta_2 - \phi_2)}$$

δ_i: Strong Phases Φ_i: Weak Phases

CPV in the B sector

Different asymmetries in terms of the weak and strong phases:

- CPV in decay:

(1) becomes
$$\mathcal{A}_f = -\frac{2|a_1 a_2| \sin(\delta_2 - \delta_1)\sin(\phi_2 - \phi_1)}{|a_1|^2 + |a_2|^2 + 2|a_1 a_2| \cos(\delta_2 - \delta_1)\cos(\phi_2 - \phi_1)}$$

extraction of $\Phi_2 - \Phi_1$ requires knowledge of the strong phase difference $\delta_2 - \delta_1$ and the amplitude ratio $|a_2/a_1|$ (non perturbative parameters)

  - Direct CPV requires two amplitudes with different phases

- CPV in mixing:

(2) becomes
$$\mathcal{A}_{SL} = -\left|\frac{\mathbf{\Gamma}_{12}}{\mathbf{M}_{12}}\right| \sin(\phi_M - \phi_\Gamma) = \frac{|\Gamma_{12}^q|}{|M_{12}^q|}\sin\phi_q$$

$$\Phi_d^{SM} = -4.9^o \pm 1.4^o$$
$$\Phi_s^{SM} = 0.24^o \pm 0.06^o$$

extraction of $\Phi_M - \Phi_\Gamma$ requires knowledge of $|\Gamma_{12} / M_{12}|$

  - CPV requires two different phases for Γ_{12} and M_{12}

CPV in the B sector

- CPV in interference between mixing and decay:
- Eigenvalue problem in the B^0 mixing gives:

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \quad \text{with} \quad |\Gamma_{12}/M_{12}| \sim 5\times 10^{-3} \rightarrow \left(\frac{q}{p}\right) \simeq e^{-i\Phi_M}$$

(neglect Γ_{12} in the expression for q/p)

therefore $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = e^{-i\Phi_M}\frac{\bar{A}_f}{A_f}$

- Assuming |q/p| = 1 (No CPV in mixing) and ΔΓ=0 (valid approximation for B^0_d):

(3) becomes $A_f(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$; $S_f = \frac{2\Im(\lambda_f)}{1+|\lambda_f|^2}$; $C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$

- S_f: CPV in interference between mixing and decay (the only CPV if $|\lambda_f| = 1$)
- C_f: CPV in decay (direct) if $|\bar{A}_f/A_f| \neq 1 \rightarrow |\lambda_f| \neq 1$

CPV in the B sector

- CPV in interference between mixing and decay:
- Eigenvalue problem in the B^0 mixing gives:

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \quad \text{with} \quad |\Gamma_{12}/M_{12}| \sim 5\times 10^{-3} \rightarrow \left(\frac{q}{p}\right) \simeq e^{-i\Phi_M}$$

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- Assuming |q/p| = 1 (No CPV in mixing) and ΔΓ=0 (valid approximation for B^0_d):

(3) becomes $A_f(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$; $S_f = \frac{2\Im(\lambda_f)}{1+|\lambda_f|^2}$; $C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$

- In the approximation of only one single weak phase in the decay: no CPV in decay

$$A_f = |a_f| e^{i(\delta_f + \Phi_f)} \rightarrow \lambda_f = \frac{q}{p} e^{-i2\Phi_f} = e^{-i(\Phi_M + 2\Phi_f)} \rightarrow |\lambda_f| = 1; \quad S_f = \Im(\lambda_f); \quad C_f = 0$$

$$A_f(t) = \Im(\lambda_f)\sin(\Delta m t), \quad \Im(\lambda_f) = \eta_f \sin(\Phi_M + 2\Phi_f)$$

$$[\eta_f : \textit{eigenvalue of the CP eigenstate } f]$$

- Insensitive to hadronic phases removed in the amplitude ratio

CPV in the B sector

- CPV in interference between mixing and decay:
- Eigenvalue problem in the B^0 mixing gives:

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \quad \text{with} \quad |\Gamma_{12}/M_{12}| \sim 5\times 10^{-3} \rightarrow \left(\frac{q}{p}\right) \simeq e^{-i\Phi_M}$$

(neglect Γ_{12} in the expression for q/p)

therefore $$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = e^{-i\Phi_M}\frac{\bar{A}_f}{A_f}$$

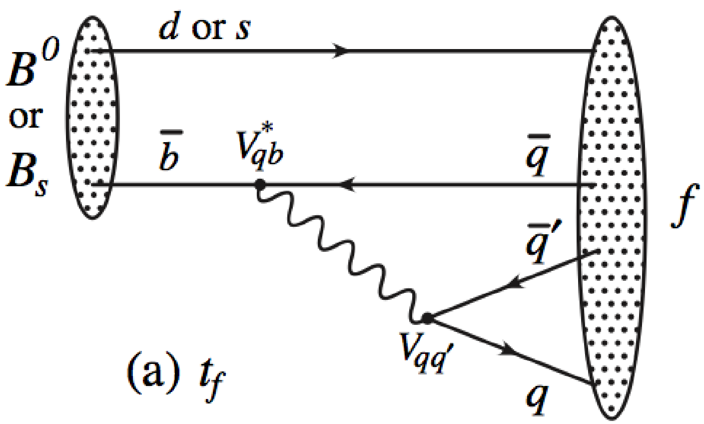
- Assuming |q/p| = 1 (No CPV in mixing) and ΔΓ=0 (valid approximation for B^0_d):

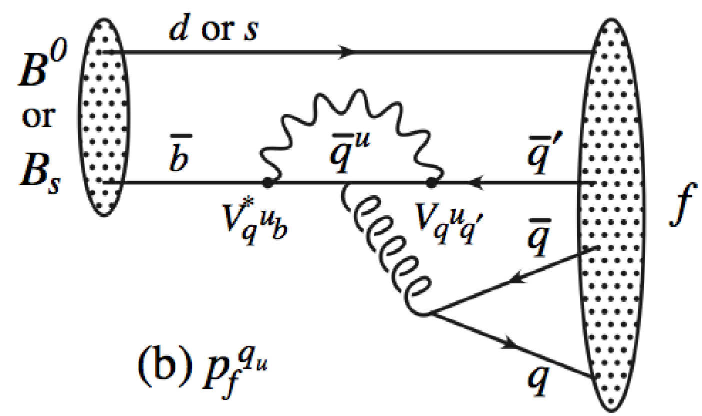
(3) becomes $$A_f(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t); \quad S_f = \frac{2\Im(\lambda_f)}{1+|\lambda_f|^2}; \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

- CPV in interference requires the mixing and the decay phases (Φ_M, Φ_f)
  - In all the three classes of CPV, two phases are present: two “weak phase” and two “strong phase” (direct CPV), the M_{12} and Γ_{12} phases (CPV in mixing), the M_{12} and the decay phases (CPV in the interference)

CPV in the Interference

- Large class of processes proceed via quark transitions $\bar{b} \to \bar{q}\, q\, \bar{q}\,', \quad q = c, u, \quad q' = s, d$
- Contribution from tree level and penguin diagrams:





$$A_f = \left(V_{qb}^* V_{qq'}\right) t_f + \sum_{q_u = u,c,t} \left(V_{q_u b}^* V_{q_u q'}\right) p_f^{q_u}$$

- Amplitude can be written in terms of just two CKM combinations (T_f & P^u):
- Ratio of CP-conjugated amplitudes for f = J/Ψ K_s, including the phase for K^0 / $\overline{K^0}$ mixing ($B^0 \to$ J/Ψ K^0, $\overline{B^0} \to$ J/Ψ $\overline{K^0}$):

$$\frac{\overline{A}_{\psi K_S}}{A_{\psi K_S}} = -\frac{\left(V_{cb} V_{cs}^*\right) T_{\psi K} + \left(V_{ub} V_{us}^*\right) P_{\psi K}^u}{\left(V_{cb}^* V_{cs}\right) T_{\psi K} + \left(V_{ub}^* V_{us}\right) P_{\psi K}^u} \times \frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}^*}$$

CPV in the Interference: β

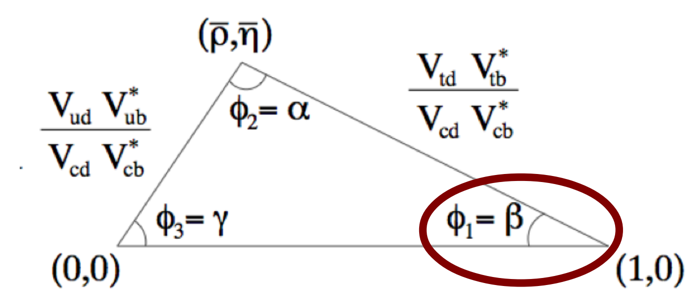
- Usually A_f includes two different weak phases → $|\lambda_f| \neq 1$: both CPV in decay and in interference: $S_f \neq 0$, $C_f \neq 0$
- If the contribution from a second phase is suppressed (see page 11): small C_f, S_f free from hadronic parameters: golden channels for measurement of CPV in interference
- Summary of $\bar{b} \to \bar{q}\, q\, \bar{q}\,'$ modes (loop: penguin/tree suppression ~ O(0.2 - 0.3), $\lambda=\sin(\theta_{Cabibbo})=0.23$)

$\bar{b} \to \bar{q}q\bar{q}'$	$B^0 \to f$	$B_s^0 \to f$	CKM dependence of A_f	Suppression
$\bar{b} \to \bar{c}c\bar{s}$	ψK_S	$\psi\phi$	$(V_{cb}^* V_{cs})T + (V_{ub}^* V_{us})P^u$	loop × λ^2

- $B^0 \to J/\Psi\, K_s$: P^u can be neglected: one single weak phase (<1% approximation):

$$\lambda_{\psi K_S} = \eta_{\psi K_S}\, e^{-i\Phi_M(B^0)} \frac{\bar{A}_{\psi K}}{A_{\psi K}} = \eta_{\psi K_S}\, e^{-2i\beta}$$

$$\to S_{\psi K_S} = -\eta_{\psi K_S} \sin 2\beta, \quad C_{\psi K_S} = 0$$



where $\beta = arg[-V_{cd}V_{cb}^* / V_{td}V_{tb}^*]$ is one of angles of the Unitarity Triangle
$\eta_{\Psi KS}$ = -1 CP eigenvalue (CP-odd)

CPV in the Interference: β

- Usually A_f includes two different weak phases → $|\lambda_f| \neq 1$: both CPV in decay and in interference: $S_f \neq 0$, $C_f \neq 0$
- If the contribution from a second phase is suppressed (see page 11): small C_f, S_f free from hadronic parameters: golden channels for measurement of CPV in interference
- Summary of $\bar{b} \to \bar{q} q \bar{q}'$ modes (loop: penguin/tree suppression ~ O(0.2 - 0.3), λ=sin($\theta_{Cabibbo}$)=0.23)

$\bar{b} \to \bar{q}q\bar{q}'$	$B^0 \to f$	$B_s^0 \to f$	CKM dependence of A_f	Suppression
$\bar{b} \to \bar{s}s\bar{s}$	ϕK_S	$\phi\phi$	$(V_{cb}^* V_{cs})P^c + (V_{ub}^* V_{us})P^u$	λ^2
$\bar{b} \to \bar{u}u\bar{s}$	$\pi^0 K_S$	K^+K^-	$(V_{cb}^* V_{cs})P^c + (V_{ub}^* V_{us})T$	λ^2/loop

- Similar situation in $\bar{b} \to \bar{s} s \bar{s}$, $\bar{b} \to \bar{u} u \bar{s}$ (few % approximation neglecting subleading contribution):
  - Look for New Physics effects from the comparison of various S_{fi} with the golden channel J/Ψ K_S result and for possible direct CPV contributions to C_{fi}
  - Effects due to hadronic parameters have to be taken into account (not complete cancellation in the amplitude ratios)

CPV in the Interference: β_s

$\bar{b} \to \bar{q}q\bar{q}'$	$B^0 \to f$	$B_s^0 \to f$	CKM dependence of A_f	Suppression
$\bar{b} \to \bar{c}c\bar{s}$	ψK_S	$\psi\phi$	$(V_{cb}^* V_{cs})T + (V_{ub}^* V_{us})P^u$	loop $\times \lambda^2$

- $B_s \to J/\Psi\ \Phi$ is analogous to $B^0 \to J/\Psi\ K_S$

- Assuming $|q/p| = 1$ (No CPV in mixing), but $\Delta\Gamma_s/\Gamma_s = 0.138 \pm 0.012$ [PDG, Chin. Phys. C38, 090001 (2014)] :

$$\mathcal{A}_f(t) = \frac{S_f \sin(\Delta m t) - C_f \cos(\Delta m t)}{\cosh(\Delta\Gamma t/2) - A_f^{\Delta\Gamma} \sinh(\Delta\Gamma t/2)}$$

where $A_f^{\Delta\Gamma} \equiv \dfrac{-2\,\mathcal{R}e(\lambda_f)}{1 + |\lambda_f|^2}$

$$\lambda_{\psi\Phi} = \eta_{\psi\Phi}\, e^{-i\Phi_M(B_s)} \frac{\bar{A}_{\psi\Phi}}{A_{\psi\Phi}} = \eta_{\psi\Phi}\, e^{-2i\beta_s}$$

$$A^{\Delta\Gamma}_{CP-even} = \cos(2\beta_s); \quad A^{\Delta\Gamma}_{CP-odd} = -\cos(2\beta_s)$$

$$\beta_s = arg[-V_{ts} V_{tb}^* / V_{cs} V_{cb}^*]$$

One of the angle of the B_s Unitarity Triangle

Usual definition $\Phi_s = -2\beta_s$

- CP asymmetry determines $\sin 2\beta_s$ analogously to $\sin 2\beta$ for $B^0 \to J/\Psi\ K_S$ with one caveat...

CPV in the Interference: β_s

- Neglecting CPV in mixing ($|q/p|=1$), mass eigenstates are CP eigenstates B_L : CP-even, B_H : CP-odd with $\Delta\Gamma=\Gamma_L - \Gamma_H>0$, $\Gamma=(\Gamma_L+\Gamma_H)/2$

  - $B_s \rightarrow J/\Psi\ \Phi$ is a Vector-Vector final state in a P-wave configuration which contains mixture of CP-even and CP-odd states (relative fraction of the two components can be affected by experimental acceptance)

  - Angular analysis needed to separate the two components provides also measurement of $\Delta\Gamma_s$

Measurement of β @ B-Factories

- Precision measurement of CP asymmetry in $B \rightarrow J/\Psi\ K_S$ (CP-odd) was the principal motivation for building the B Factories

- Other $b \rightarrow c\bar{c}s$ channels: $J/\Psi\ K_L$ (CP-even), $\Psi(2S)K_S$, $\eta_c K_S$, $\chi_{c1} K_S$, $J/\Psi\ K^{*0}$ (Vector-Vector final state, orbital angular momentum L=0, 1, 2 requires angular analysis)

- Alternative measurements from other transitions: $b \rightarrow s\bar{s}s$ ($B \rightarrow \Phi K_S$), $b \rightarrow c\bar{c}d$ ($D^{(*)+}D^{(*)-}$): angular analysis needed

- Most precise measurements from $b \rightarrow c\bar{c}s$: experimentally clean signals (CKM favored, color suppressed), theoretically clean (deviation due to penguin with different weak phase < 1%)

Measurement of β @ B-Factories

Belle Measurement using $B^0 \rightarrow (c\bar{c})K^0$ decays (772×10^6 BB)

[Phys. Rev. Lett. 108, 171802 (2012)]

- Decay chain $\Upsilon(4S) \rightarrow B^0\bar{B}^0 \rightarrow f_{CP}\ f_{tag}$
  - One B^0 decays at time t_{CP} to a CP eigenstate f_{CP}
    - CP-odd: $J/\Psi\ K_S$, $\Psi(2S)K_S$, $\chi_{c1}K_S$
    - CP-even: $J/\Psi\ K_L$
  - Other B^0 decays at time t_{tag} to a flavor eigenstate f_{tag}
  - Decay rate in the $\Upsilon(4S)$ rest frame:

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 + q[S_f \sin(\Delta m_d \Delta t) + C_f \cos(\Delta m_d \Delta t)]\}.$$

$$\Delta t = t_{CP} - t_{tag} = \Delta_z / (\beta\gamma c);\quad \beta = 0.425$$

Lorentz Boost

$$q = +1(-1)\ for\ B^0(\bar{B}^0)$$

- SM predicts:

$$S_f = -\eta_f \sin(2\beta),\quad C_f = 0 \quad \beta = arg[-V_{cd}V_{cb}^* / V_{td}V_{tb}^*]$$

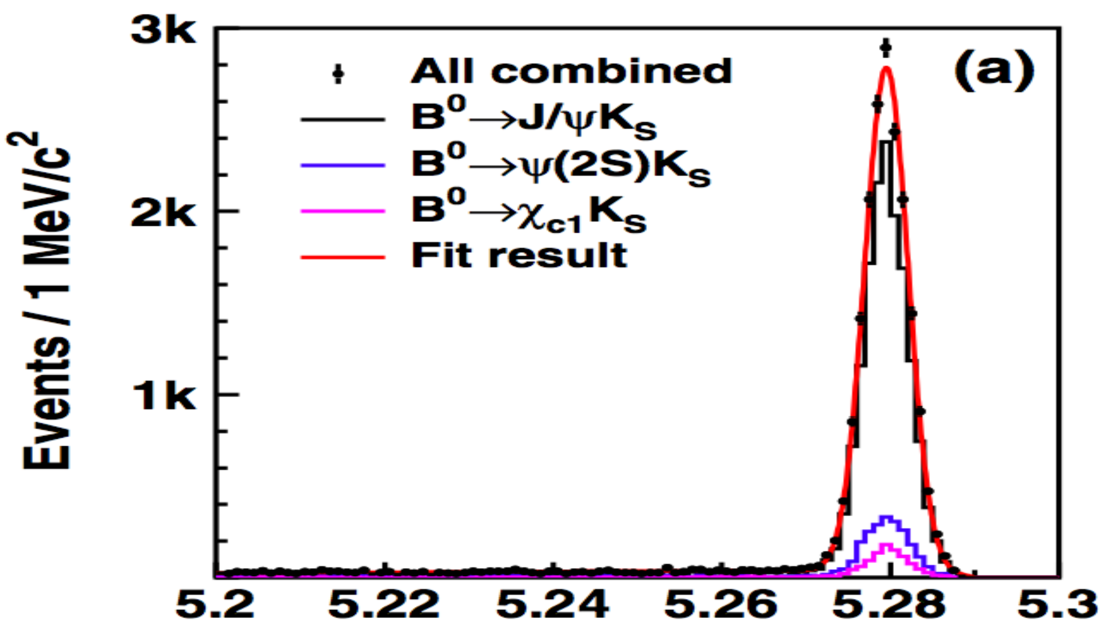
$$\eta_f = +1(-1)\ for\ CP-even(odd)$$

Measurement of β @ B-Factories

Belle Measurement using $B^0 \rightarrow (c\bar{c})K^0$ decays (772×10^6 BB)

[Phys. Rev. Lett. 108, 171802 (2012)]

- Charmonia recostruction: $J/\Psi \rightarrow l^+l^-$ (l=e, μ), $\Psi \rightarrow l^+l^-$, $\chi_{c1} \rightarrow J/\Psi\gamma$
- $K_S \rightarrow \pi^+\pi^-$ selected exploiting invariant mass, flight length, angle between flight direction and momentum
- $B \rightarrow X K_S$ candidate reconstructed using ΔE and m_{ES}



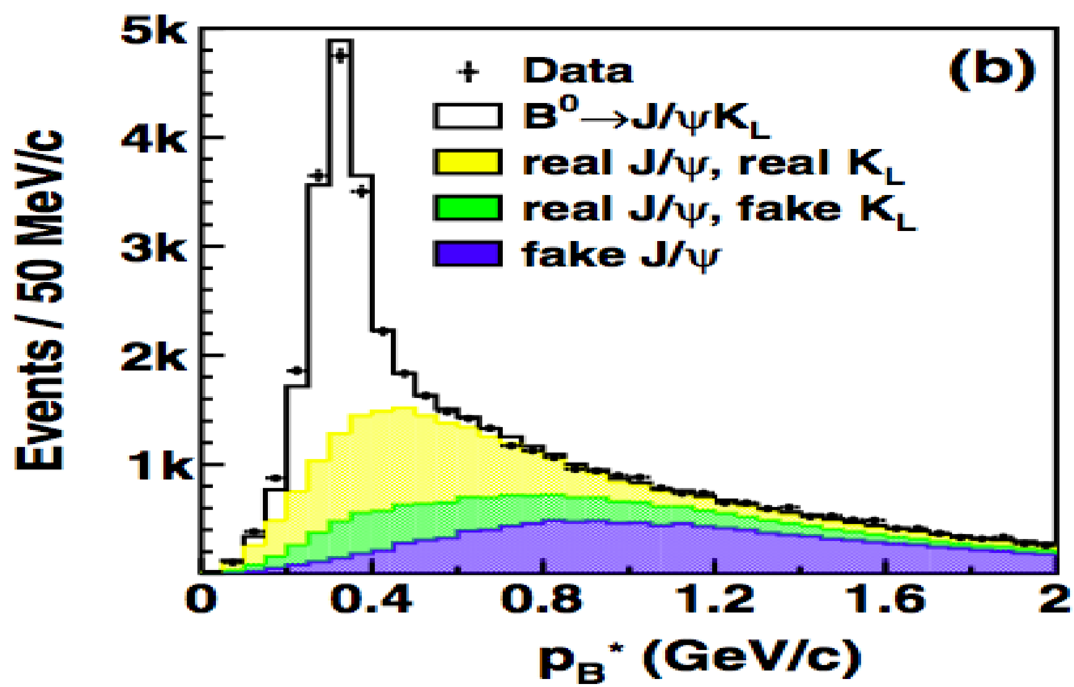
m_{ES} (GeV)

Measurement of β @ B-Factories

Belle Measurement using $B^0 \to (c\bar{c})K^0$ decays (772×10^6 BB)

[Phys. Rev. Lett. 108, 171802 (2012)]

- Charmonia recostruction: $J/\Psi \to l^+l^-$ ($l=e, \mu$), $\Psi \to l^+l^-$, $\chi_{c1} \to J/\Psi\gamma$
- K_L selected from calorimeter and muon detector hit patterns
- $B \to J/\Psi K_L$ selected by means of p^*_B in the ϒ(4S) rest frame computed based on reconstructed J/Ψ & two bodies kinematics



Measurement of β @ B-Factories

Belle Measurement using $B^0 \to (c\bar{c})K^0$ decays (772 x 10^6 BB)

[Phys. Rev. Lett. 108, 171802 (2012)]

Flavor tagging

- Use inclusive properties of particles not associated with the $B^0 \to f_{CP}$
- Tagging information defined by two output parameters:
  - B_{tag} flavor q (+1 for B^0, -1 for $\overline{B}^0$)
  - Event by event flavor assignment based on multiple discriminants

$$\varepsilon_{\rm tag} = \frac{\varepsilon_{B^0} + \varepsilon_{\overline{B}^0}}{2}$$

$$w = \frac{w_{B^0} + w_{\overline{B}^0}}{2}$$

$$\Delta\varepsilon_{\rm tag} = \varepsilon_{B^0} - \varepsilon_{\overline{B}^0}$$

$$\Delta w = w_{B^0} - w_{\overline{B}^0}$$

$$Q = \varepsilon_{\rm tag}(1 - 2w)^2$$

Sub-tagger	$Q_{\rm abs}$ on MC
Leptons	12%
Kaons and Λ's	18%
Slow Pions	6%

Q_{total}=29.8±0.4%

Measurement of β @ B-Factories

Belle Measurement using $B^0 \to (c\bar{c})K^0$ decays (772×10^6 BB)

[Phys. Rev. Lett. 108, 171802 (2012)]

Δt Reconstruction

- f_{CP} vertex from well reconstructed J/Ψ; f_{tag} vertex from tracks not associated to f_{CP}
- Constraint using the 2D IP profile in the (x, y) plane allows vertex with just one track (12% in B_{CP}, 23% in B_{tag})
- Resolution function obtained convolving four components:
  - Experimental smearing on z_{CP} & z_{tag}
  - z_{tag} bias due to tracks from $D^{(*)}$ decays (move in the ϒ(4S) direction)
  - Boost Approximation: B at rest in ϒ(4S) rest frame, neglect B decay length
- Resolution function parameters from a high-statistic control sample of semileptonic and hadronic $b \to c$ decays

Measurement of β @ B-Factories

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- Constraint using the 2D IP profile in the (x, y) plane allows vertex with just one track (12% in B_{CP}, 23% in B_{tag})

- Signal yields from unbinned maximum-likelihood fit to (ΔE, m_{ES}) (K_S) or p^*_B (K_L)
- BKG from:
  - $B \rightarrow J/\Psi X$ (estimated from MC): real J/Ψ & K_L, real J/Ψ and fake K_L, fake J/Ψ
  - Combinatorial (from J/Ψ side bands)

Decay mode	ξ_f	N_{sig}	Purity (%)
$J/\psi K^0_S$	−1	12 649 ± 114	97
$\psi(2S)(\ell^+\ell^-)K^0_S$	−1	904 ± 31	92
$\psi(2S)(J/\psi\pi^+\pi^-)K^0_S$	−1	1067 ± 33	90
$\chi_{c1}K^0_S$	−1	940 ± 33	86
$J/\psi K^0_L$	+1	10 040 ± 154	63

Measurement of β @ B-Factories

Belle Measurement using $B^0 \rightarrow (c\bar{c})K^0$ decays (772 x 10^6 BB)

[Phys. Rev. Lett. 108, 171802 (2012)]

- S_f, C_f obtained from an unbinned maximum-likelihood fit to the Δt distribution including mistag and resolution

- BKG: sum of exponential and prompt components convolved with 2-Gaussian Resolution Function
- PDF for event i:

$$P_i = (1 - f_{\rm ol})\sum_k f_k \int [\mathcal{P}_k(\Delta t')R_k(\Delta t_i - \Delta t')]d(\Delta t') + f_{\rm ol}P_{\rm ol}(\Delta t_i),$$

- Fractions of various components from the (ΔE, m_{ES}) (K_S) or p^*_B (K_L) fits; ol: outlier broad gaussian (0.5% of the sample)

Decay mode	$\sin 2\phi_1 \equiv -\xi_f S_f$	C_f
$J/\psi K_S^0$	$+0.670 \pm 0.029 \pm 0.013$	$-0.015 \pm 0.021^{+0.045}_{-0.023}$
$\psi(2S)K_S^0$	$+0.738 \pm 0.079 \pm 0.036$	$+0.104 \pm 0.055^{+0.047}_{-0.027}$
$\chi_{c1}K_S^0$	$+0.640 \pm 0.117 \pm 0.040$	$-0.017 \pm 0.083^{+0.046}_{-0.026}$
$J/\psi K_L^0$	$+0.642 \pm 0.047 \pm 0.021$	$+0.019 \pm 0.026^{+0.017}_{-0.041}$
All modes	$+0.667 \pm 0.023 \pm 0.012$	$+0.006 \pm 0.016 \pm 0.012$

Measurement of β @ B-Factories

Belle Measurement using $B^0 \rightarrow (c\bar{c})K^0$ decays (772×10^6 BB)

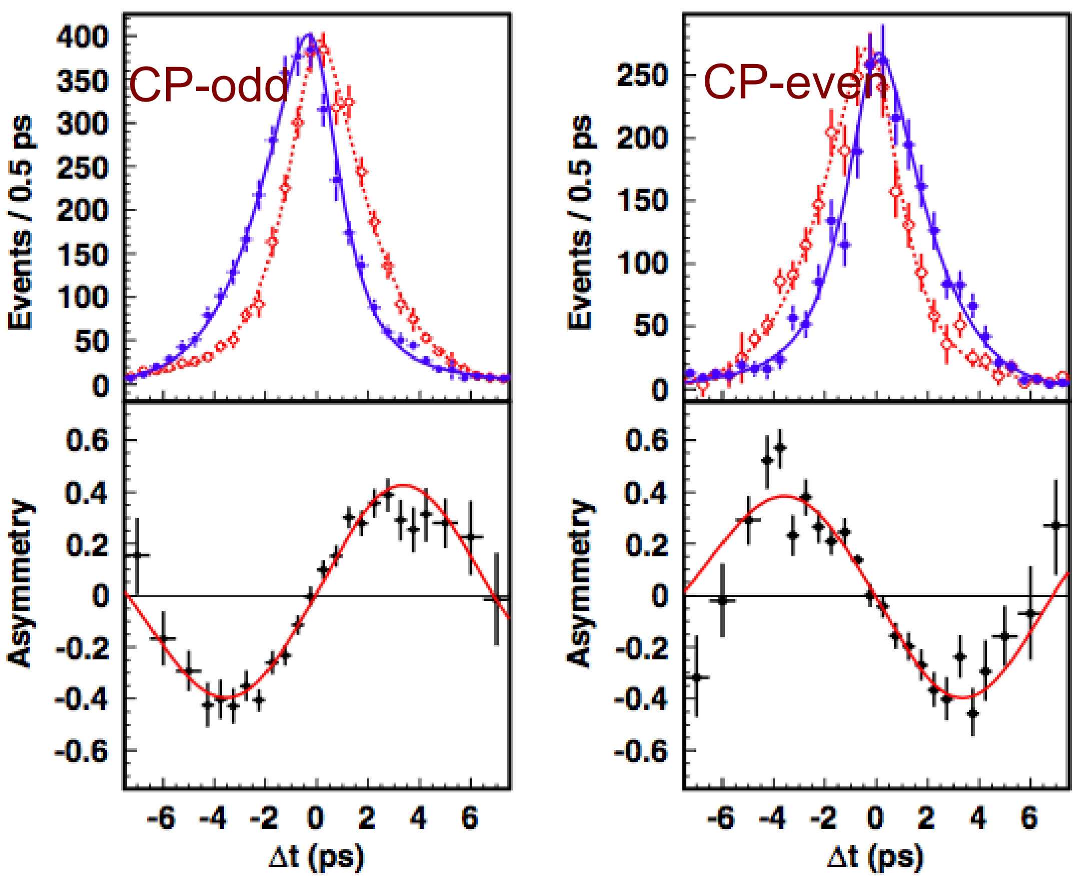
[Phys. Rev. Lett. 108, 171802 (2012)]

$$A(\Delta t) = \frac{N_+ - N_-}{N_+ + N_-}$$

$$\sin 2\beta = 0.667 \pm 0.023 \pm 0.012$$

$$C_f = 0.006 \pm 0.016 \pm 0.012$$

$B^0\,tag$, $\bar{B}^0\,tag$



- Most precise sin 2β measurement
- No direct CPV
- Systematics dominated by vertexing & Δt resolution:
  - Quality cuts on vertex, minimum distance from CP vertex for tracks to be included in the tag vertex
  - Vary resolution function parameters

Measurement of β @ B-Factories

		$J/\psi K_S^0$	$\psi(2S)K_S^0$	$\chi_{c1}K_S^0$	$J/\psi K_L^0$	All
Vertexing	$\mathcal{S}_f$	±0.008	±0.031	±0.025	±0.011	±0.007
	$\mathcal{A}_f$	±0.022	±0.026	±0.021	±0.015	±0.007
Δt resolution	$\mathcal{S}_f$	±0.007	±0.007	±0.005	±0.007	±0.007
	$\mathcal{A}_f$	±0.004	±0.003	±0.004	±0.003	±0.001
Tag-side interference	$\mathcal{S}_f$	±0.002	±0.002	±0.002	±0.001	±0.001
	$\mathcal{A}_f$	${}^{+0.038}_{-0.000}$	${}^{+0.038}_{-0.000}$	${}^{+0.038}_{-0.000}$	${}^{+0.000}_{-0.037}$	±0.008
Flavor tagging	$\mathcal{S}_f$	±0.003	±0.003	±0.004	±0.003	±0.004
	$\mathcal{A}_f$	±0.003	±0.003	±0.003	±0.003	±0.003
Possible fit bias	$\mathcal{S}_f$	±0.004	±0.004	±0.004	±0.004	±0.004
	$\mathcal{A}_f$	±0.005	±0.005	±0.005	±0.005	±0.005
Signal fraction	$\mathcal{S}_f$	±0.004	±0.016	<0.001	±0.016	±0.004
	$\mathcal{A}_f$	±0.002	±0.006	<0.001	±0.006	±0.002
Background Δt PDFs	$\mathcal{S}_f$	<0.001	±0.002	±0.030	±0.002	±0.001
	$\mathcal{A}_f$	<0.001	<0.001	±0.014	<0.001	<0.001
Physics parameters	$\mathcal{S}_f$	±0.001	±0.001	±0.001	±0.001	±0.001
	$\mathcal{A}_f$	<0.001	<0.001	±0.001	<0.001	<0.001
Total	$\mathcal{S}_f$	±0.013	±0.036	±0.040	±0.021	±0.012
	$\mathcal{A}_f$	${}^{+0.045}_{-0.023}$	${}^{+0.047}_{-0.027}$	${}^{+0.046}_{-0.026}$	${}^{+0.017}_{-0.041}$	±0.012

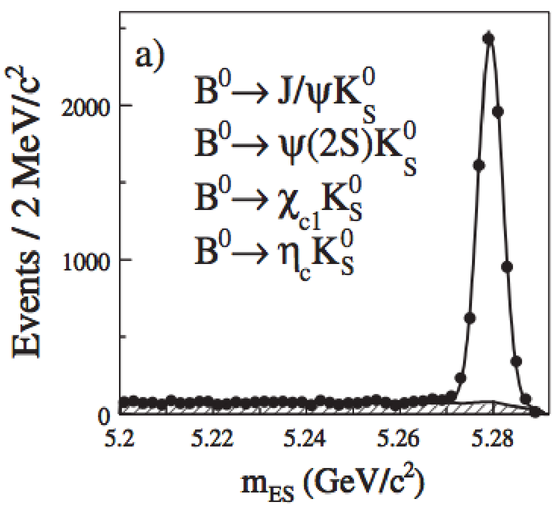
- Systematics dominated by vertexing & Δt resolution:
  - Quality cuts on vertex, minimum distance from CP vertex for tracks to be included in the tag vertex
  - Vary resolution function parameters

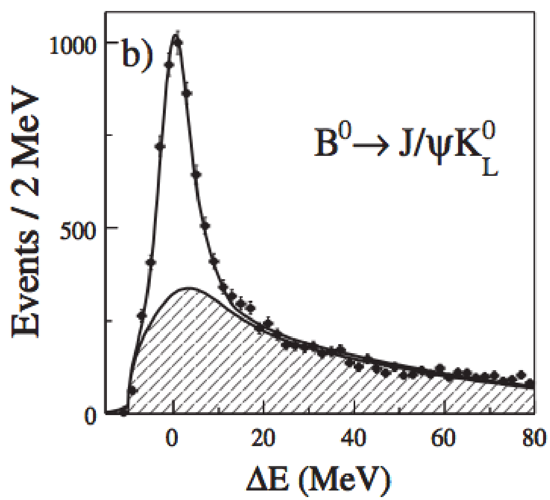
Measurement of β @ B-Factories

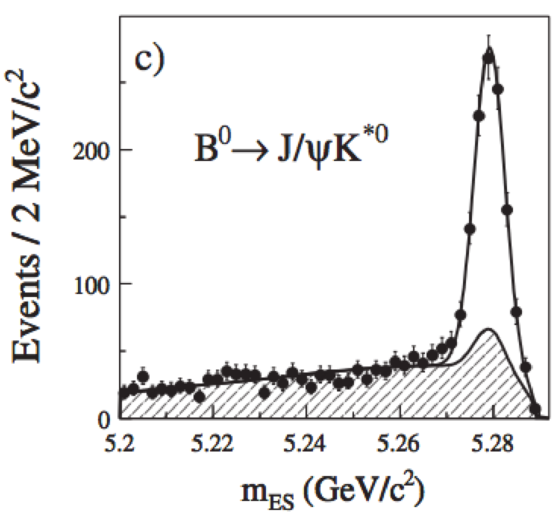
BaBar Meas. using $B^0 \rightarrow (cc)K^{(*)0}$ decays (465×10^6 BB)

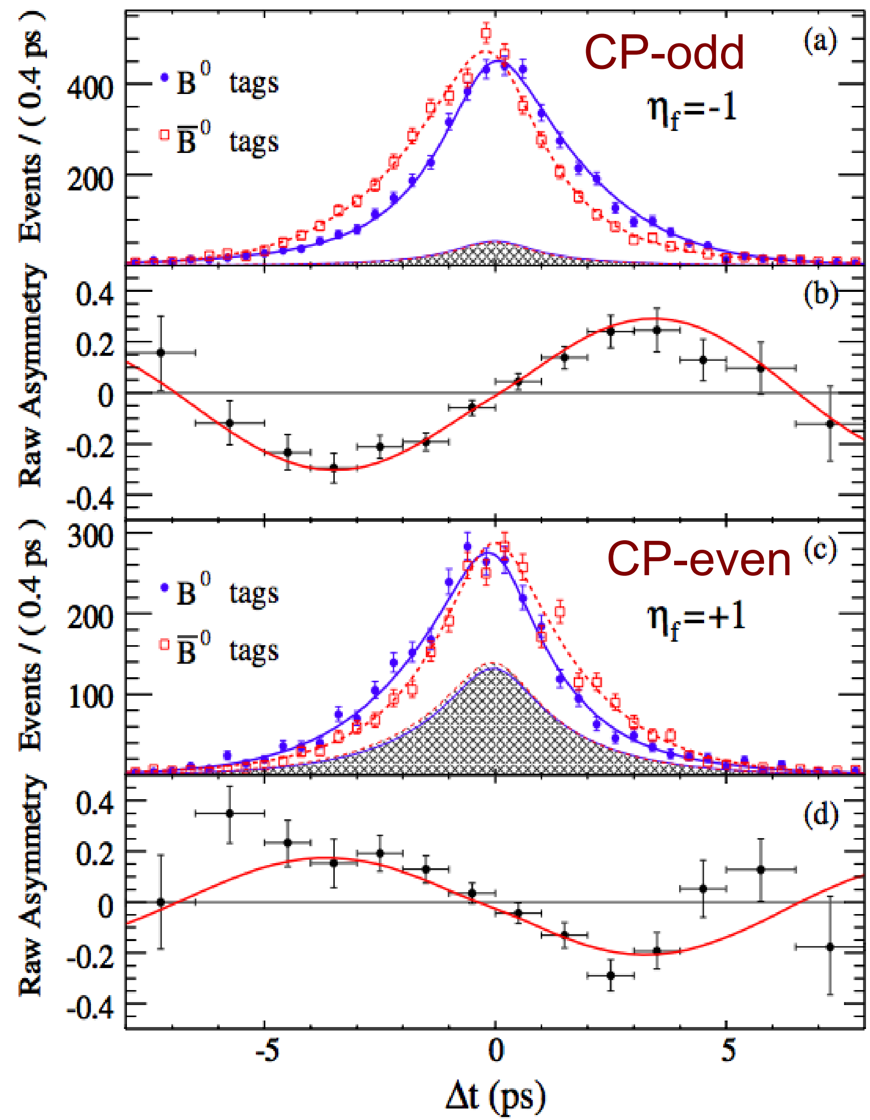
[Phys. Rev. D. 79, 072009 (2009)]

- From similar analysis









Measurement of β @ B-Factories

BaBar Meas. using $B^0 \rightarrow (c\bar{c})K^{(*)0}$ decays (465 x 10^6 $B\bar{B}$)

[Phys. Rev. D. 79, 072009 (2009)]

- From similar analysis

- $J/\Psi K^{*0}$ admixture of CP-odd and CP-even can be separated by angular analysis

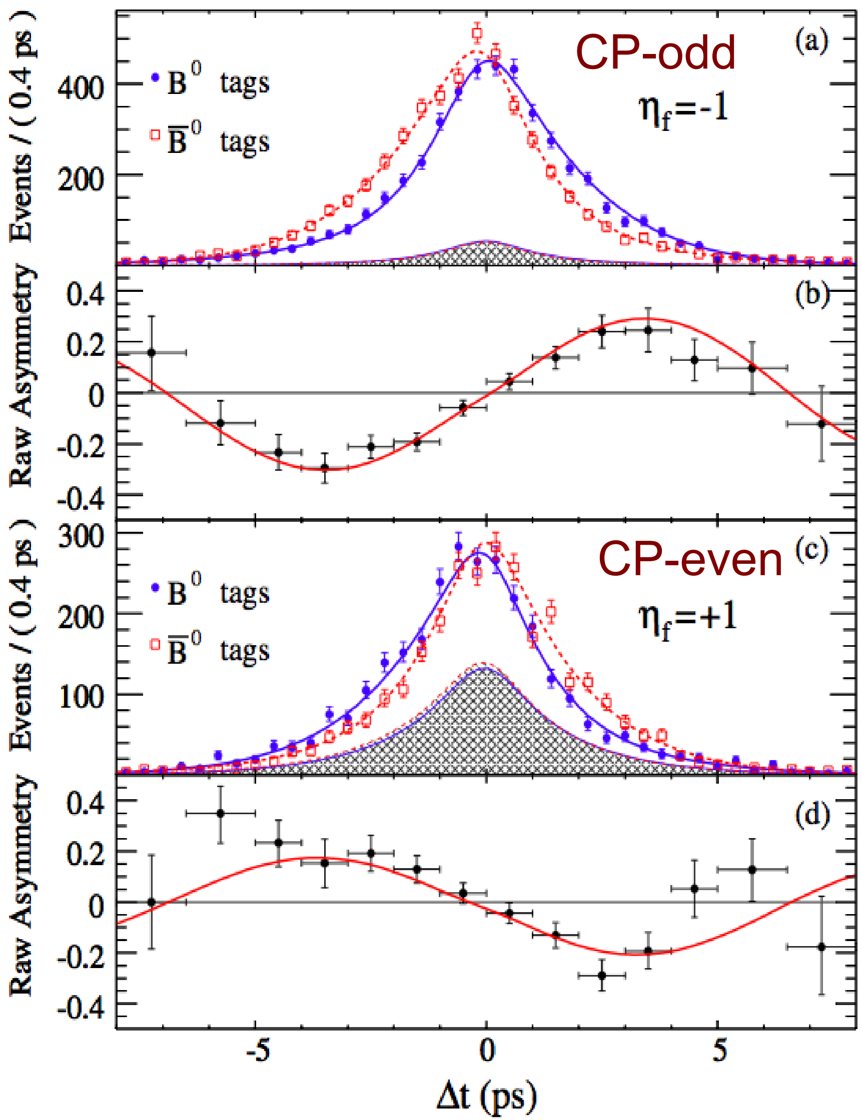
- In this analysis average computed resulting in a dilution = 1-2R, R=23.3±1.0±0.5% fraction of L=1 (CP-odd) contribution
  [Phys Rev. D 76 031102(R) (2007)]

- Effective η_f=0.504±0.033

$$A(\Delta t) = \frac{N_+ - N_-}{N_+ + N_-}; \quad +: B^0 tag, \quad -: \bar{B}^0 tag$$

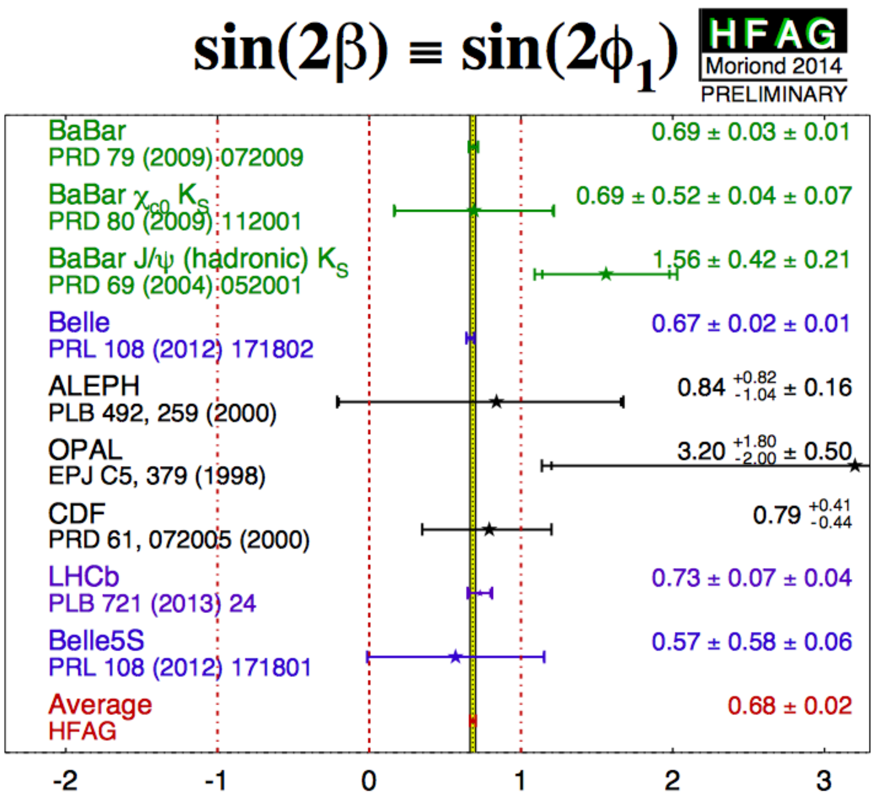
$$\sin 2\beta = 0.687 \pm 0.028 \pm 0.012$$

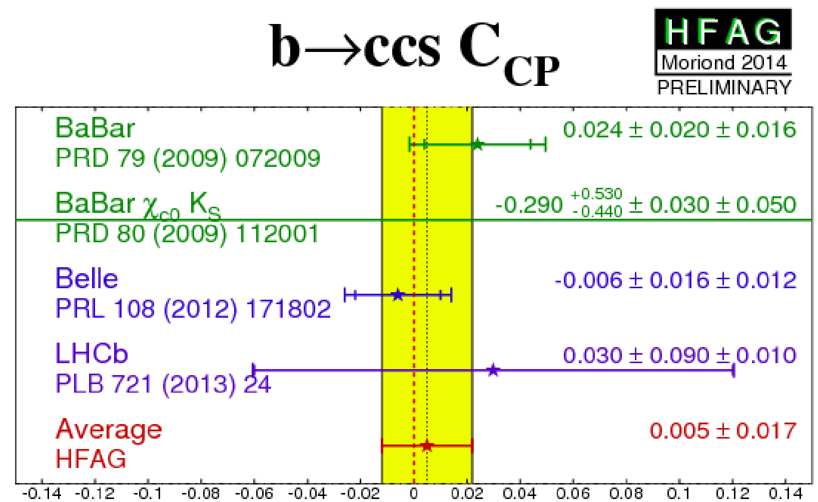
$$C_f = 0.024 \pm 0.020 \pm 0.016$$



Measurement of β

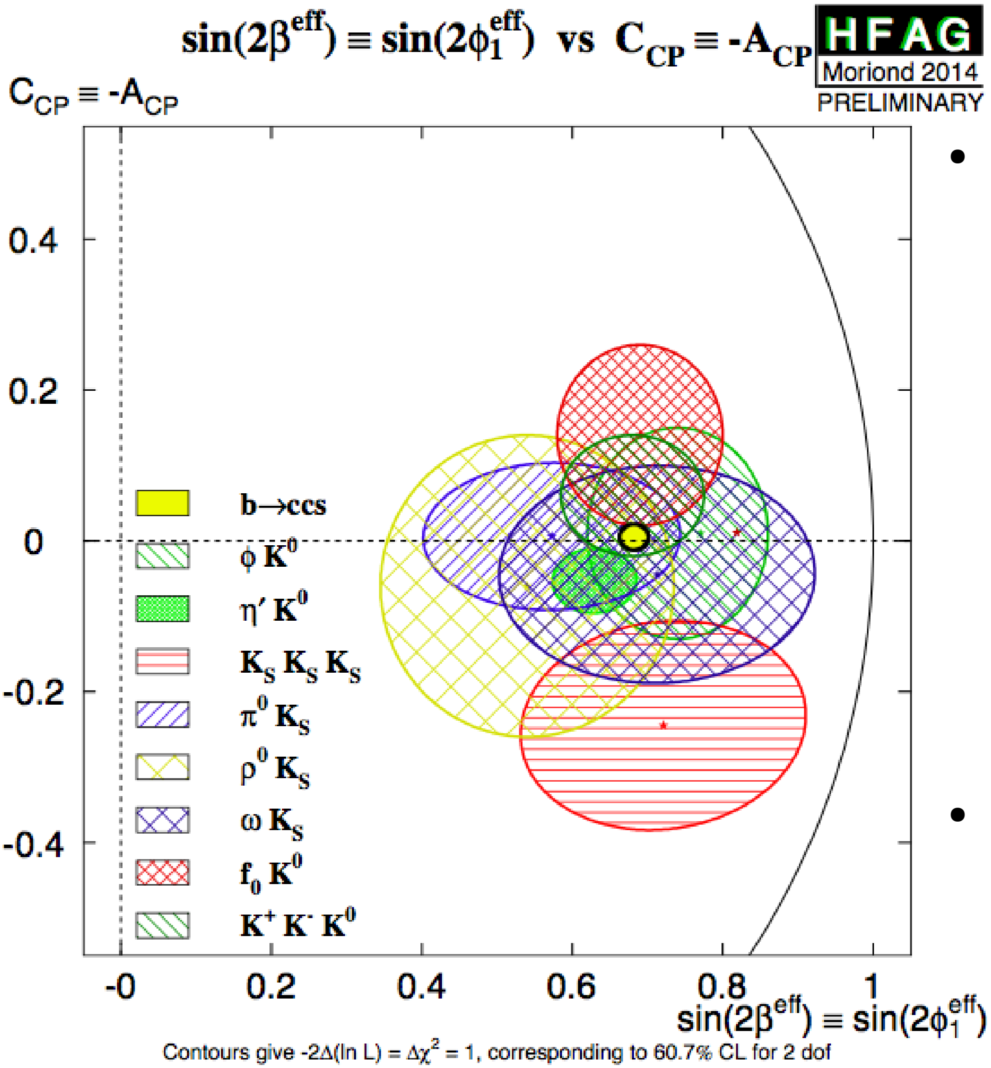
Results using $b \to c\bar{c}s$





- Results consistent with negligible P^u term: no direct CPV (C~0)

Measurement of β

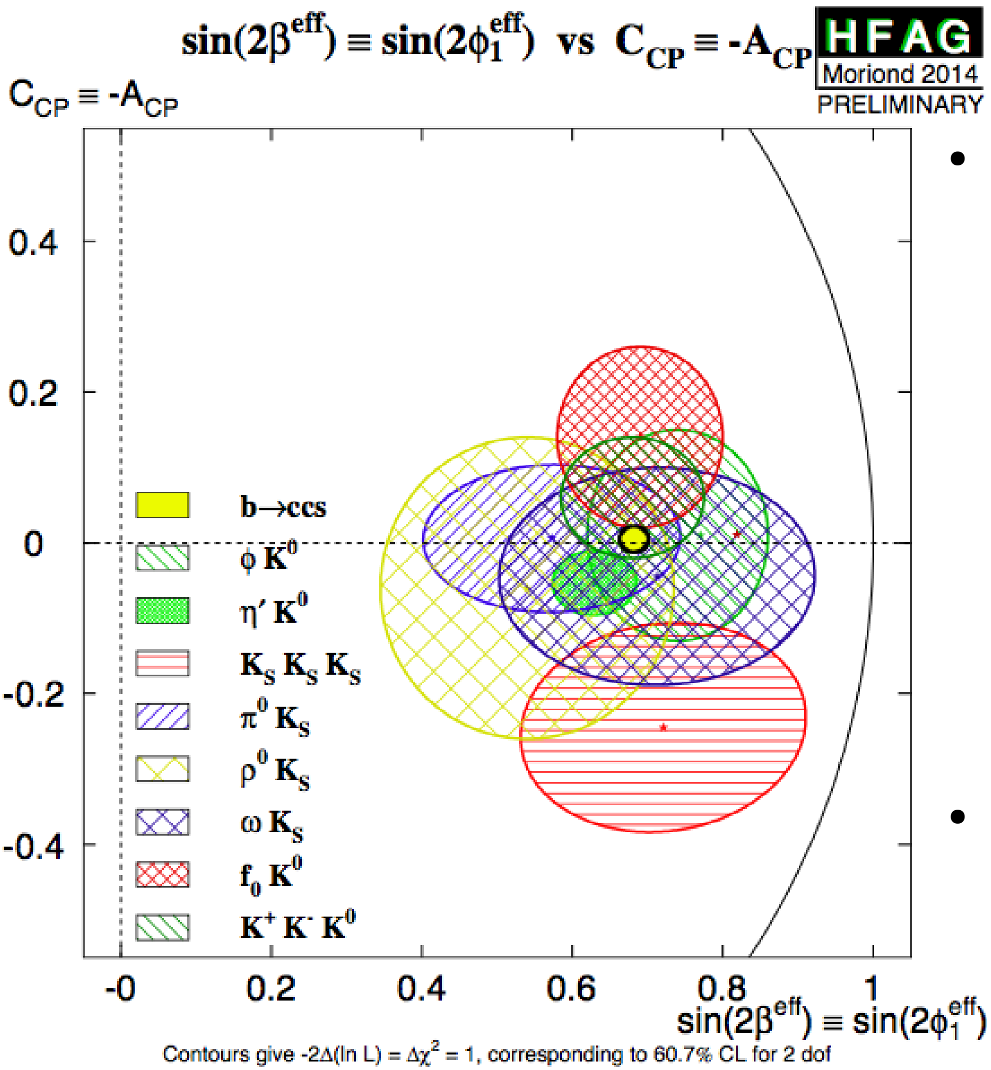


- Several other channels suppressed wrt golden one have been studied
  - Tree dominated modes with a penguin or a second tree with different phase ($b \to c\bar{c}d$: $J/\Psi\pi^0$, $D^{(*)}D^{(*)}$)
  - Charmless modes $b \to q\bar{q}s$ (q=u, d, s) penguin-dominated, very sensitive to new heavy particles in the loops
    - Most precise $B^0 \to \eta' K^0$, $K^+K^-K^0$: $\delta(\sin 2\beta) \sim 0.07$

- Check for:
  - S_f different from $J/\Psi K_S$
  - S_f different for different final states
  - C_f different from zero

- Consistency with the SM predictions shows CKM mechanism is the dominant source of CPV in the quark sector

Measurement of β



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- Check for:
  - S_f different from $J/\Psi K_S$
  - S_f different for different final states
  - C_f different from zero

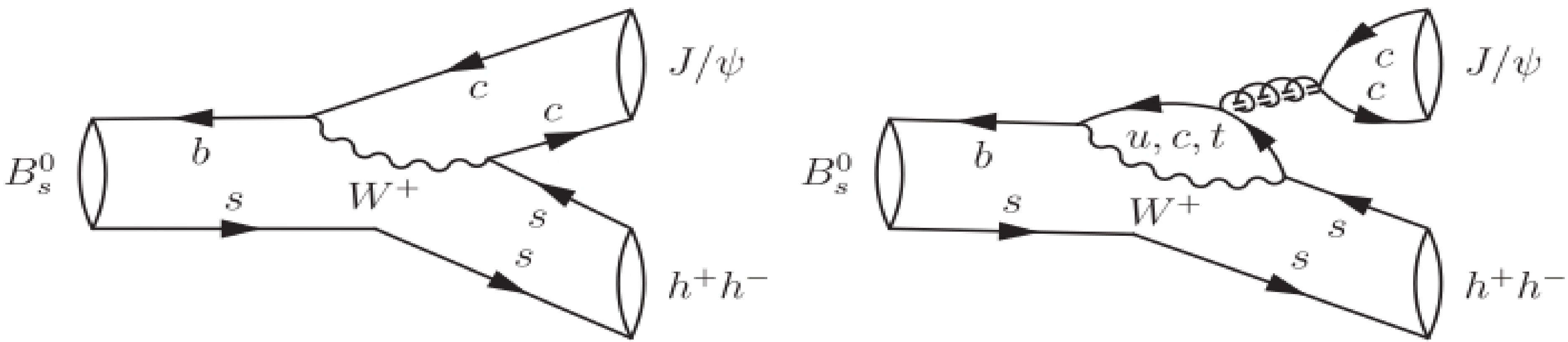
- Interpretation of possible differences would be difficult due to hadronic parameteres
- Good agreement implies little room for New Physics in this sector

Measurement of β_s & $\Delta\Gamma_s$ @ LHCb

Measurement using $B_s \to J/\Psi K^+K^-$, $J/\Psi\pi^+\pi^-$ (L=3 fb^{-1})

[Phys. Rev. Lett. 114, 041801 (2015)]

- Indirect determination via global fits to experimental data gives $\Phi_s=-2\beta_s=-0.0363\pm0.0013$ rad [J. Charles et al., Phys. Rev. D 84, 033005 (2011)]



- $B_s \to J/\Psi K^+K^-$ dominated by $B_s \to J/\Psi\Phi$, $\Phi \to KK$
- Intermediate Vector-Vector meson state → KK in a P-wave configuration
  - Superposition of CP-even and CP-odd eigenstates depending on the relative orbital angular momentum of the two Vector mesons
  - Same final state can be produced by KK in an S-wave configuration (CP-odd)
- Phase measurement requires CP-even and CP-odd components to be disentangled by the analysis of the decay angles of the final state particles
- Analysis provides also Γ & $\Delta\Gamma$ measurements

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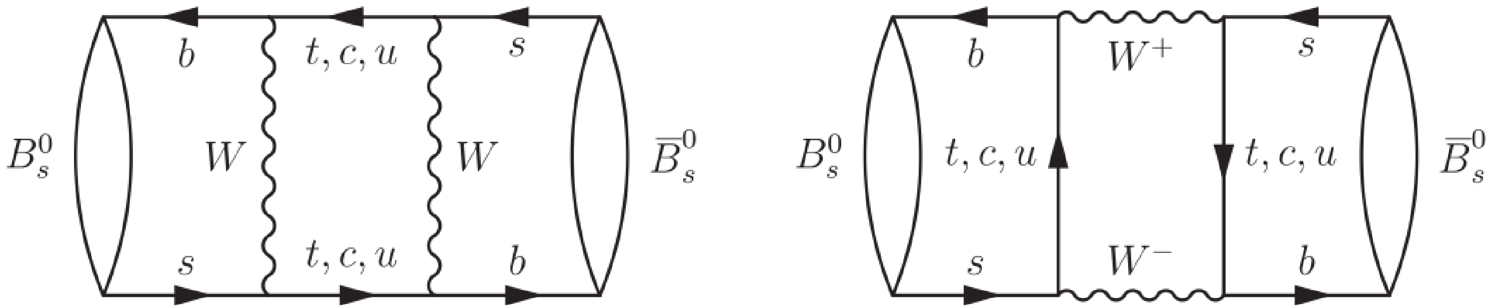
- New particle exchange in the box diagrams could modify the SM phase



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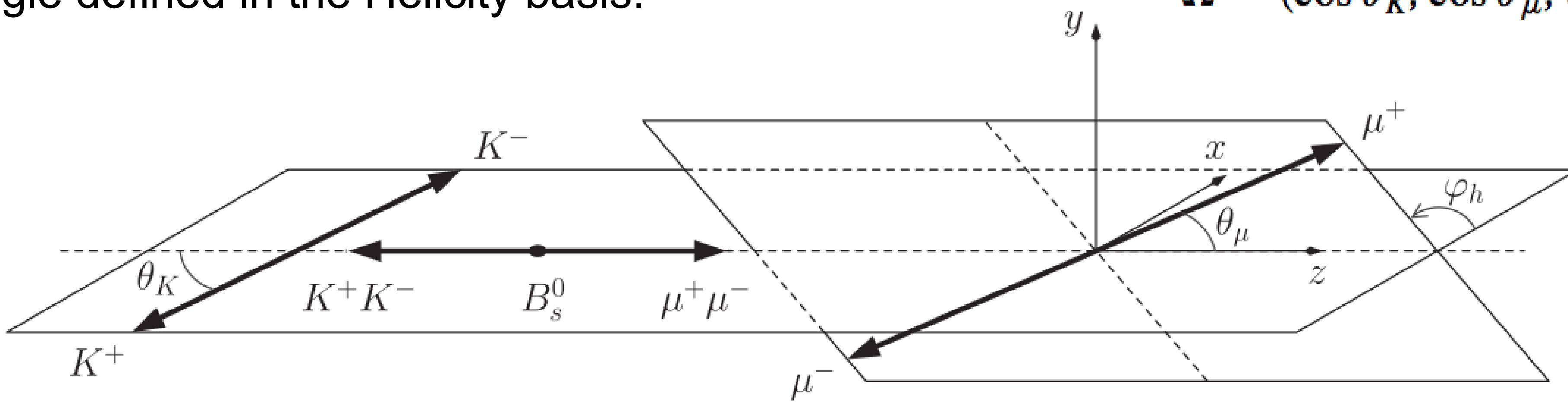
Measurement of β_s & $\Delta\Gamma_s$ @ LHCb

Measurement using $B_s \rightarrow J/\Psi K^+K^-$, $J/\Psi \pi^+\pi^-$ (L=3 fb^{-1})

[Phys. Rev. Lett. 114, 041801 (2015)]

Angle defined in the Helicity basis: $\Omega = (\cos\theta_K, \cos\theta_\mu, \varphi_h)$



- Decay decomposed into 4 time-dependent complex amplitudes $A_i(t) = |A_i(t)| e^{i\delta_i}$
  - Three (P-wave decay) describe the relative orientation of the polarization vectors of the J/Ψ and Φ:
    $i \in \{0, \parallel, \perp\}$: longitudinal (CP-even), transverse-parallel (CP-even), transverse-perpendicular (CP-odd)
  - One, $A_s(t)$ describes the KK S-wave amplitude (CP-odd)

Measurement of β_s & $\Delta\Gamma_s$ @ LHCb

Measurement using $B_s \rightarrow J/\Psi K^+K^-$, $J/\Psi\pi^+\pi^-$ (L=3 fb^{-1})

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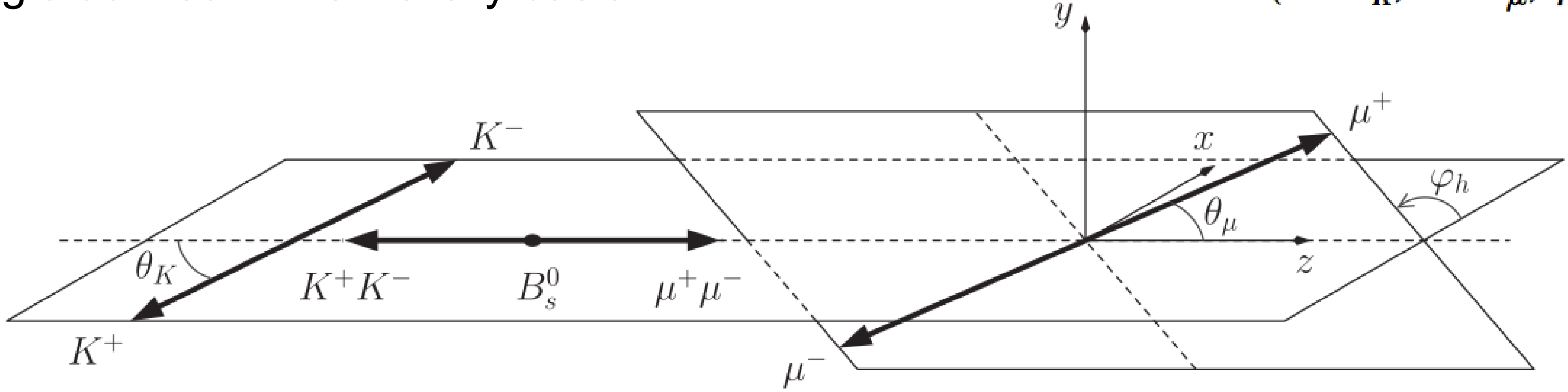

- Decay decomposed into 4 time-dependent complex amplitudes $A_i(t)=|A_i(t)|e^{i\delta_i}$
- Conventions:
  - $\delta_0=0$
  - $|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1.$
  - $F_S \doteq |A_S|^2/(|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 + |A_S|^2) = |A_S|^2/(|A_S|^2 + 1).$

Measurement of β_s & $\Delta\Gamma_s$ @ LHCb

Measurement using $B_s \rightarrow J/\Psi K^+K^-$, $J/\Psi \pi^+\pi^-$ ($L=3\ fb^{-1}$)

[Phys. Rev. Lett. 114, 041801 (2015)]

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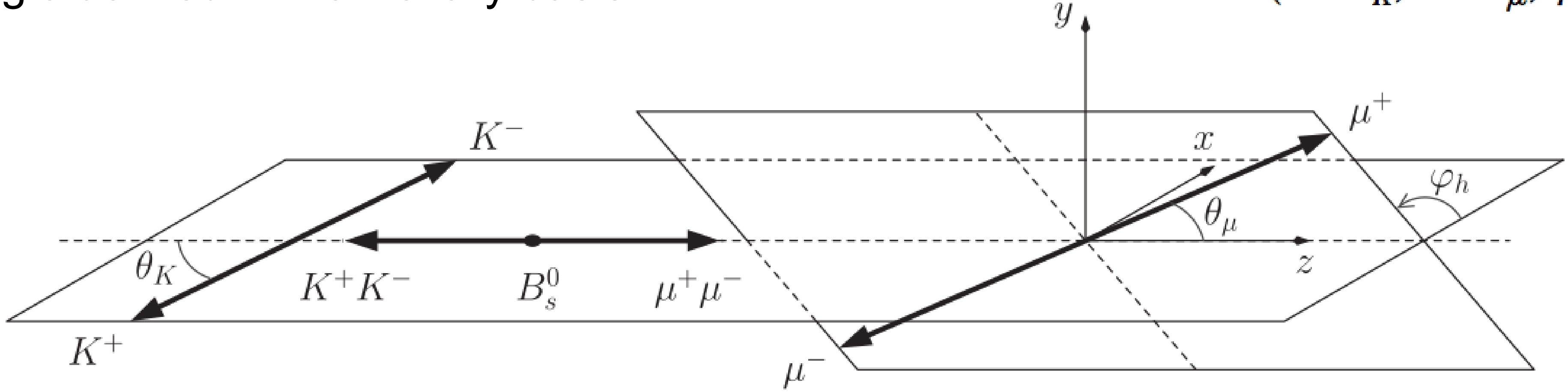


- Differential rate described by a sum of 10 terms (different amplitudes and their interference terms)
  [Dighe et al., Phys. Lett. B 369, 144 (1996), Duniez et al., Phys. Rev. D 63, 114015 (2001), Xie et al., JHEP 09, 074 (2009)]

$$\frac{d^4\Gamma(B_s^0 \rightarrow J/\psi K^+K^-)}{dt\,d\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega).$$

$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\frac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\frac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right],$$

Measurement of β_s & $\Delta\Gamma_s$ @ LHCb

Measurement using $B_s \rightarrow J/\Psi K^+K^-$, $J/\Psi\pi^+\pi^-$ (L=3 fb^{-1})

[Phys. Rev. Lett. 114, 041801 (2015)]

k	$f_k(\theta_\mu, \theta_K, \varphi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\|A_0\|^2$	1	D	C	$-S$
2	$\sin^2\theta_K(1-\sin^2\theta_\mu \cos^2\varphi_h)$	$\|A_\parallel\|^2$	1	D	C	$-S$
3	$\sin^2\theta_K(1-\sin^2\theta_\mu \sin^2\varphi_h)$	$\|A_\perp\|^2$	1	$-D$	C	S
4	$\sin^2\theta_K \sin^2\theta_\mu \sin 2\varphi_h$	$\|A_\parallel A_\perp\|$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K \sin 2\theta_\mu \cos\varphi_h$	$\|A_0 A_\parallel\|$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K \sin 2\theta_\mu \sin\varphi_h$	$\|A_0 A_\perp\|$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\|A_S\|^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \cos\varphi_h$	$\|A_S A_\parallel\|$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \sin\varphi_h$	$\|A_S A_\perp\|$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\theta_K \sin^2\theta_\mu$	$\|A_S A_0\|$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

$$\frac{d^4\Gamma(B_s^0 \rightarrow J/\psi K^+K^-)}{dt\,d\Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega).$$

$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\frac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\frac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right],$$

- Rate for $\overline{B}_s$ obtained by changing the sign of c_k and d_k and including a relative factor $|p/q|^2$

$$S = \frac{2\,\Im(\lambda_f)}{1+|\lambda_f|^2}; \quad C = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}; \quad D = A_f^{\Delta\Gamma} = \frac{-2\,\Re(\lambda_f)}{1+|\lambda_f|^2}$$

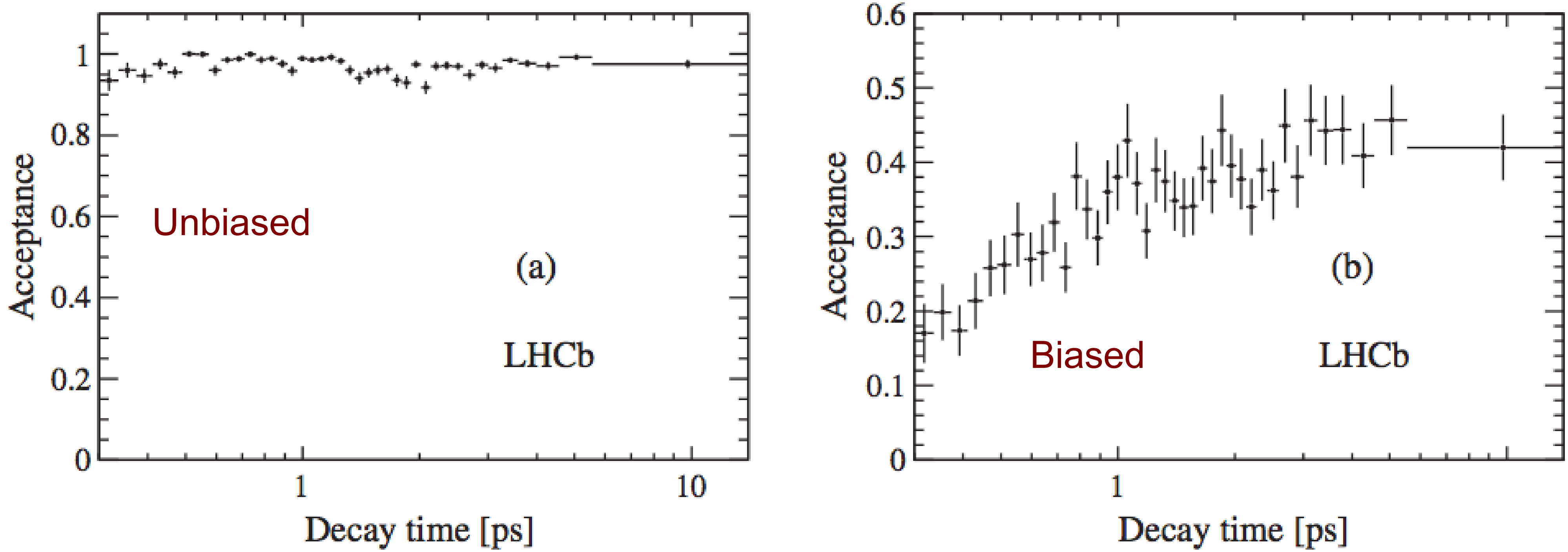
Measurement of β_s & $\Delta\Gamma_s$ @ LHCb

Measurement using $B_s \rightarrow J/\Psi K^+K^-$, $J/\Psi\pi^+\pi^-$ ($L=3\ fb^{-1}$)

[Phys. Rev. Lett. 114, 041801 (2015)]

Alternative Trigger requirements:

- Two muons with $m(\mu^+\mu^-)>2.7$ GeV: uniform in decay time: "Unbiased" sample
- At least one muon with $p_T > 1$ GeV & IP > 100 μm wrt PV: nontrivial acceptance in decay time: "Biased" sample



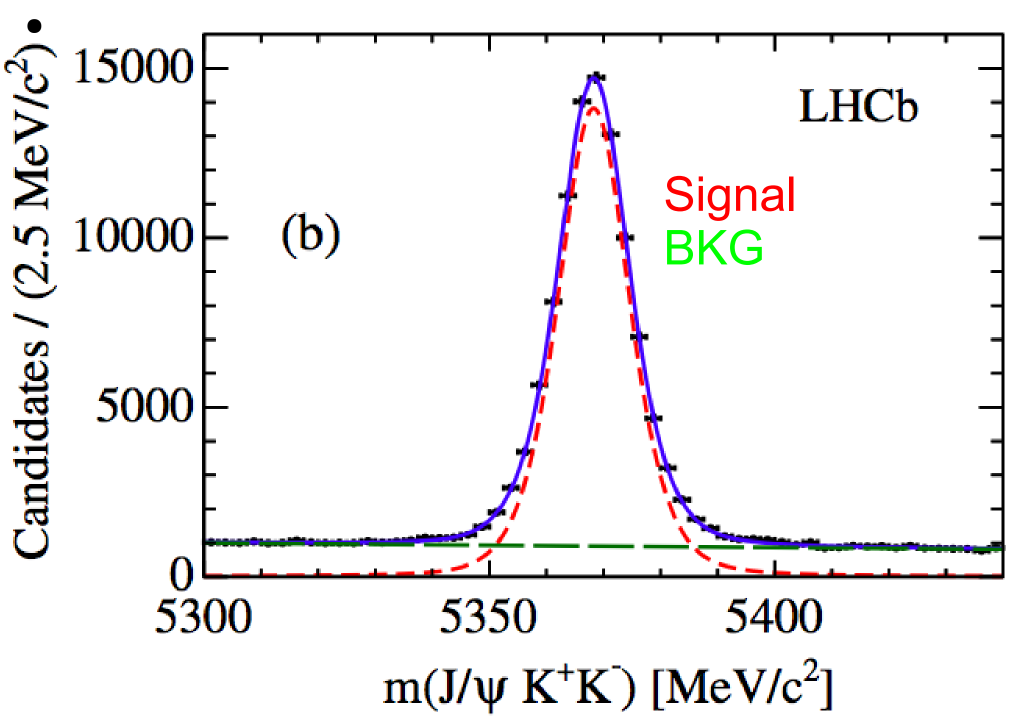
Measurement of β_s & $\Delta\Gamma_s$ @ LHCb

Measurement using $B_s \to J/\Psi K^+K^-$, $J/\Psi \pi^+\pi^-$ ($L=3\ fb^{-1}$)

[Phys. Rev. Lett. 114, 041801 (2015)]

- B selection:
  - $p_T(\mu_{1,2})$> 500 MeV
  - $m(\mu^+\mu^-)$=[3030,3150] MeV
  - $p_T(K_{1,2})$>1 GeV
  - $m(K^+K^-)$=[990,1050] MeV

- BKG from $B^0 \to J/\Psi K\pi$, $\Lambda_b \to J/\Psi Kp$ statistically subtracted by adding reweighted MC events with negative weight



- Flavor Tagging by means of:
  - Opposite-side tagger: Q=(2.55±0.14)%
  - Same-side Kaon tagger using a Neural Network: Q=(1.26±0.14)%
  - 26% of events have both taggers: Combined tagging power Q=(3.73±0.15)%

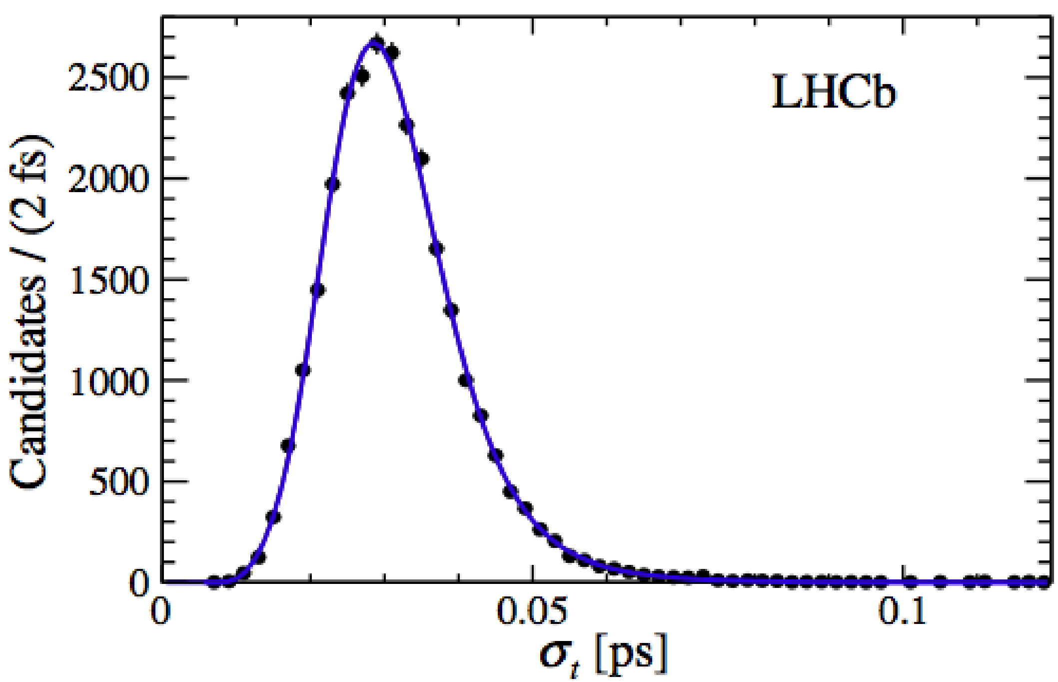
Measurement of β_s & $\Delta\Gamma_s$ @ LHCb

Measurement using $B_s \rightarrow J/\Psi K^+K^-$, $J/\Psi\pi^+\pi^-$ (L=3 fb^{-1})

[Phys. Rev. Lett. 114, 041801 (2015)]

Decay Time

- Oscillation period T=3.5 10^{-13} s
- Decay time from the secondary vertex fit constraining the B_s to originate from its associated Primary Vertex using a χ^2 cut
  - 0.3 ps < t < 14.0 ps suppresses prompt BKG
  - σ_t < 0.12 ps



- σ_t depends on vertex and momentum resolution
- Resolution R(t;σt) modeled by a sum of two Gaussians with a common offset and different scale factors

Measurement of β_s & $\Delta\Gamma_s$ @ LHCb

Measurement using $B_s \to J/\Psi K^+K^-$, $J/\Psi\pi^+\pi^-$ ($L=3\ fb^{-1}$)

[Phys. Rev. Lett. 114, 041801 (2015)]

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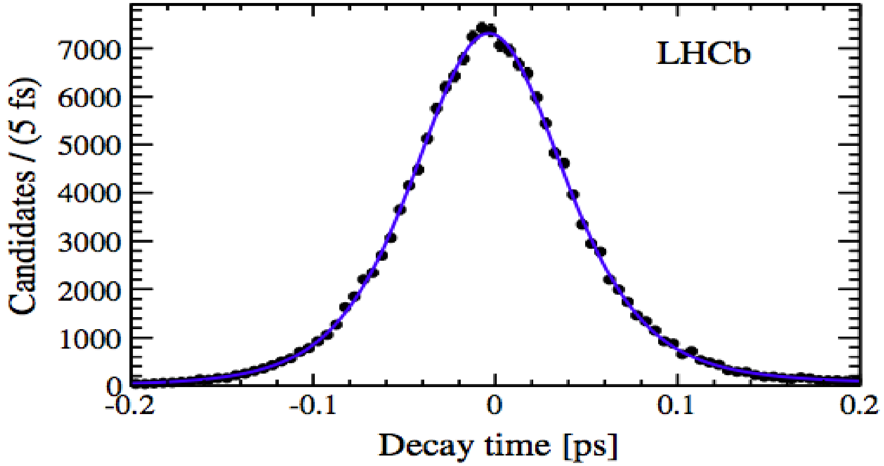
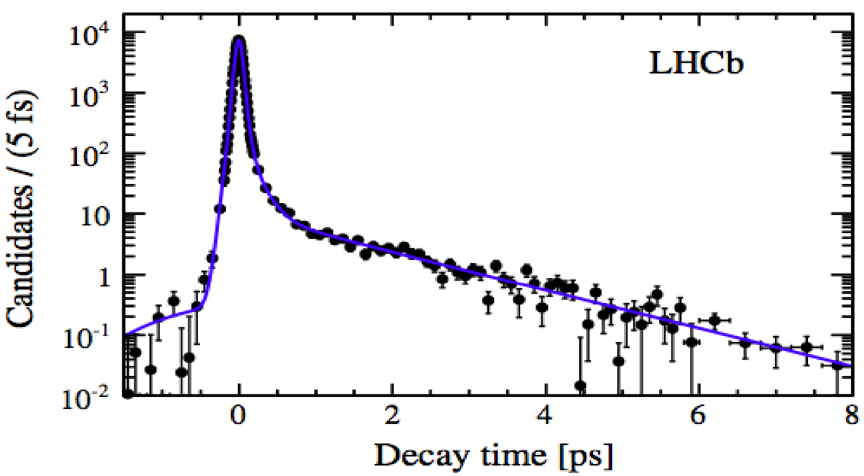
- Decay time from the secondary vertex fit constraining the B_s to originate from its associated Primary Vertex using a χ^2 cut
  - $0.3\ ps < t < 14.0\ ps$ suppresses prompt BKG
  - $\sigma_t < 0.12\ ps$
  - Scale factors from a sample of prompt fake $J/\Psi(\mu^+\mu^-)K^+K^-$ candidates with zero true decay time
  - Resulting effective $<\sigma_t> = 46$ fs
  - Decay time distribution distorted by acceptance function due to tracks with large IP. Determined from $B^+ \to J/\Psi K^+$



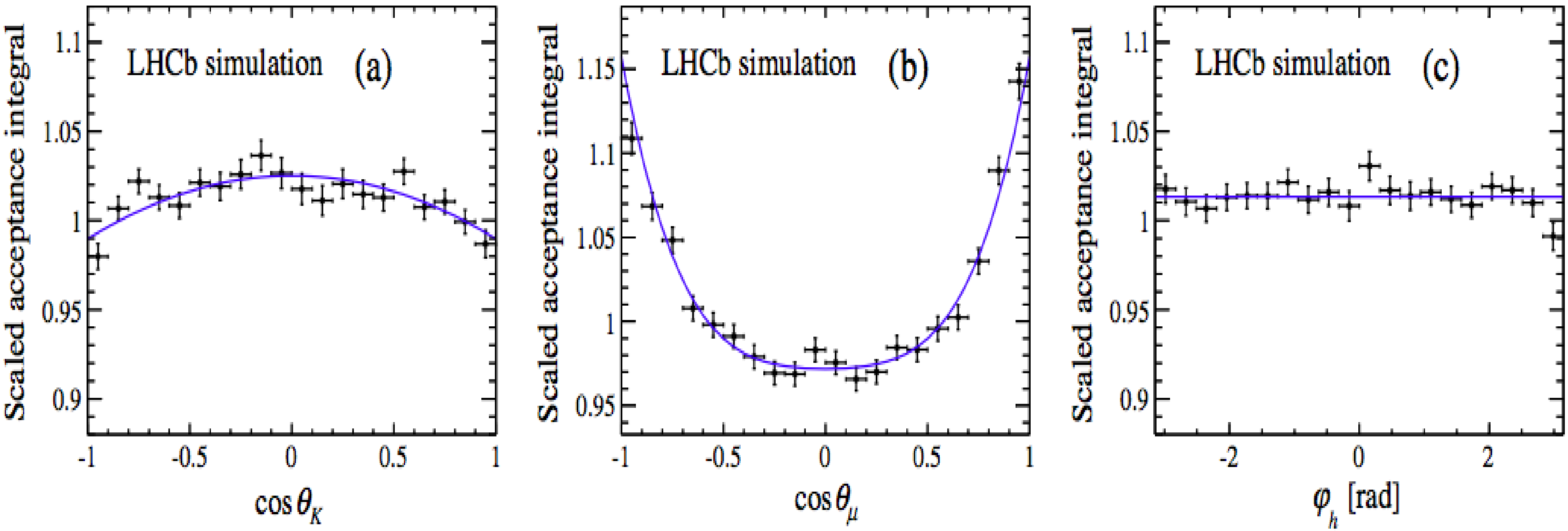


Measurement of β_s & $\Delta\Gamma_s$ @ LHCb

Measurement using $B_s \to J/\Psi K^+K^-$, $J/\Psi\pi^+\pi^-$ (L=3 fb^{-1})

[Phys. Rev. Lett. 114, 041801 (2015)]

Angular Acceptance

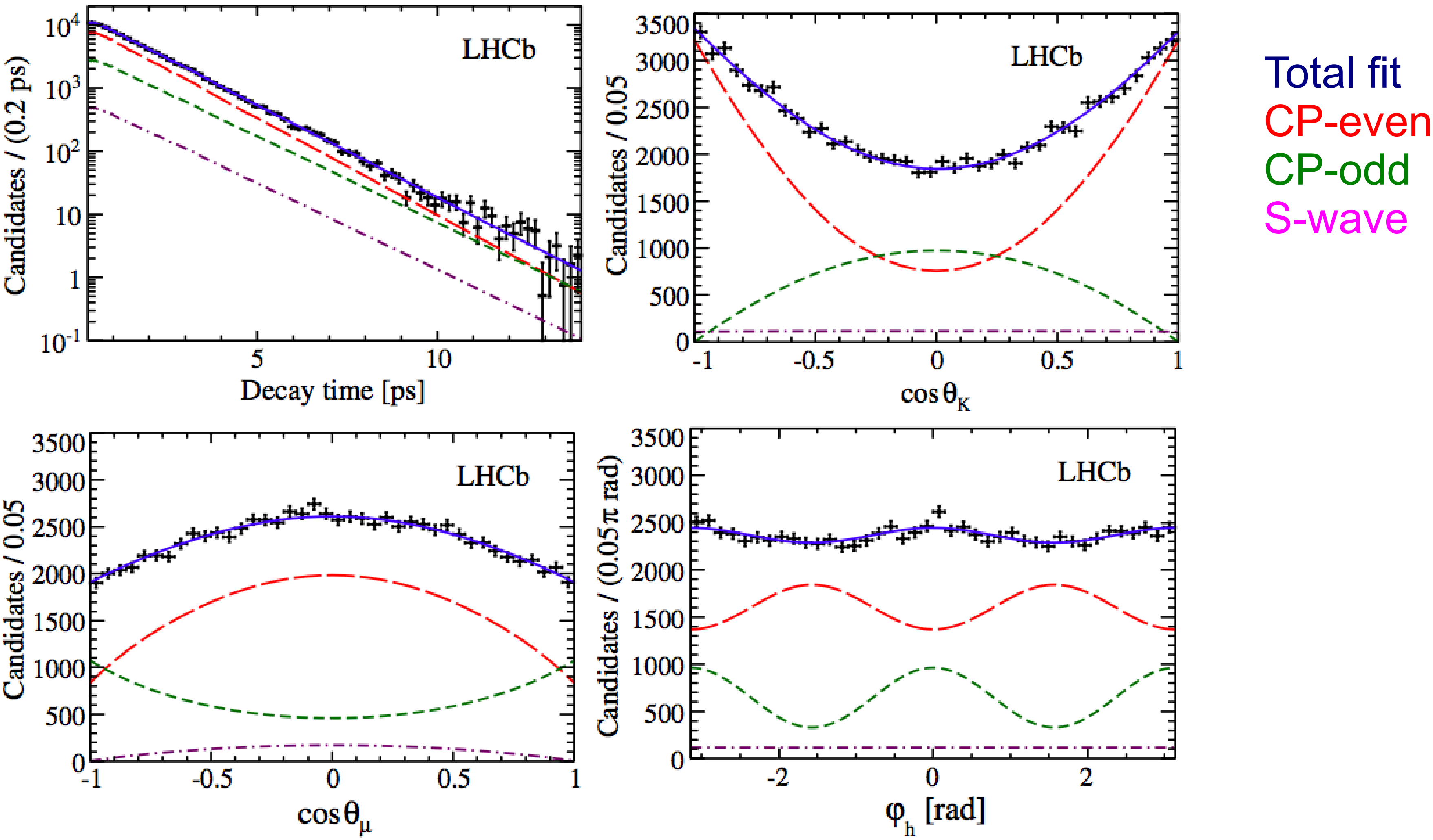


- Angular acceptance functions ε_Ω not uniform due to the forward geometry of the detector and requirements on particle momenta
  - Effect dominated by $p_T(\mu)$ cut
  - Effect determined on MC with particle momentum reweighting to match the data spectrum

Measurement of β_s & $\Delta\Gamma_s$ @ LHCb

$X = \frac{d^4\Gamma(B_s^0 \to J/\Psi KK)}{dt\, d\Omega}$; $\bar{X} = \frac{d^4\Gamma(\bar{B}_s^0 \to J/\Psi KK)}{dt\, d\Omega}$; *Fit :* $\Gamma_s, \Delta\Gamma_s, |A_0|^2, |A_\perp|^2, F_s, \delta_\parallel, \delta_\perp, \delta_s, |\lambda|, \Delta m_s$

$$\Omega = (\cos\theta_K, \cos\theta_\mu, \varphi_h)$$



Measurement of β_s & $\Delta\Gamma_s$ @ LHCb

[Phys. Rev. Lett. 114, 041801 (2015)]

- Fit results for $B_s \to J/\psi KK$

Parameter	Value
Γ_s (ps^{-1})	$0.6603 \pm 0.0027 \pm 0.0015$
$\Delta\Gamma_s$ (ps^{-1})	$0.0805 \pm 0.0091 \pm 0.0032$
$\|A_\perp\|^2$	$0.2504 \pm 0.0049 \pm 0.0036$
$\|A_0\|^2$	$0.5241 \pm 0.0034 \pm 0.0067$
$\delta_\parallel$ (rad)	$3.26^{+0.10}_{-0.17}{}^{+0.06}_{-0.07}$
$\delta_\perp$ (rad)	$3.08^{+0.14}_{-0.15} \pm 0.06$
ϕ_s (rad)	$-0.058 \pm 0.049 \pm 0.006$
$\|\lambda\|$	$0.964 \pm 0.019 \pm 0.007$
Δm_s (ps^{-1})	$17.711^{+0.055}_{-0.057} + 0.011$

- Adding $B_s \to J/\psi\pi\pi$

$$\Phi_s = 0.070 \pm 0.068 \pm 0.008\, rad$$

- Most precise measurement

$$\to \Phi_s = -0.010 \pm 0.039\, rad$$

- Systematics
  - Angular acceptance: from MC reweighting of K momentum & MC statistics
  - Decay time resolution offset: left free or fixed to zero in the fit
  - $B^0 \to J/\Psi K^*$ Peaking BKG with $\pi \to K$: estimated from simulation

Measurement of β_s & $\Delta\Gamma_s$ @ LHCb

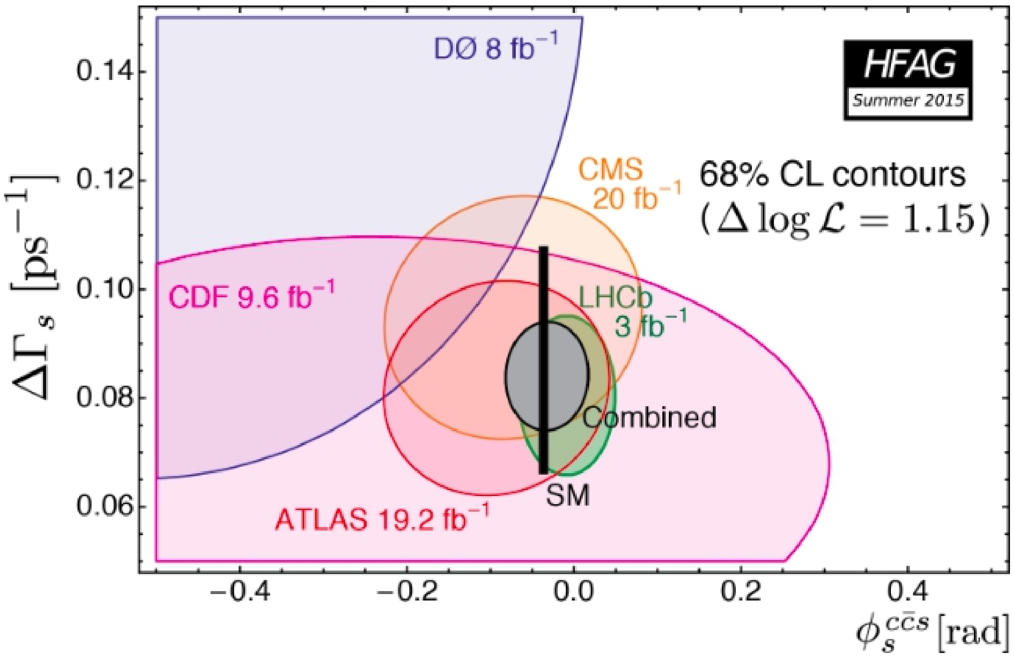
[Phys. Rev. Lett. 114, 041801 (2015)]

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\|A_\perp\|^2$	$\|A_0\|^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\|\lambda\|$
Statistical uncertainty	0.0048	0.016	0.0086	0.0061	$^{+0.13}_{-0.21}$	0.22	0.091	0.031
Background subtraction	0.0041	0.002	···	0.0031	0.03	0.02	0.003	0.003
$B^0 \to J/\psi K^{*0}$ background	···	0.001	0.0030	0.0001	0.01	0.02	0.004	0.005
Angular acceptance reweighting	0.0007	···	0.0052	0.0091	0.07	0.05	0.003	0.020
Angular acceptance statistical	0.0002	···	0.0020	0.0010	0.03	0.04	0.007	0.006
Lower decay-time acceptance model	0.0023	0.002	···	···	···	···	···	···
Upper decay-time acceptance model	0.0040	···	···	···	···	···	···	···
Length and momentum scales	0.0002	···	···	···	···	···	···	···
Fit bias	···	···	0.0010	···	···	···	···	···
Decay-time resolution offset	···	···	···	···	···	0.04	0.006	···
Quadratic sum of systematics	0.0063	0.003	0.0064	0.0097	0.08	0.08	0.011	0.022
Total uncertainties	0.0079	0.016	0.0107	0.0114	$^{+0.15}_{-0.23}$	0.23	0.092	0.038

- Systematics
  - Angular acceptance: from MC reweighting of K momentum & MC statistics
  - Decay time resolution offset: left free or fixed to zero in the fit
  - $B^0 \to J/\Psi K^*$ Peaking BKG with $\pi \to K$: estimated from simulation

Measurement of β_s & $\Delta\Gamma_s$

World Average [http://www.slac.stanford.edu/xorg/hfag/osc/summer_2015/HFAG_phis_inputs.pdf]



$$\Delta\Gamma_s = 0.084 \pm 0.007\ ps^{-1}$$
$$\Phi_s = -0.034 \pm 0.033\ rad$$

In good agreement with SM expectations [Lenz, Nierste, arXiv:1102.4274, J. Charles et al., Phys. Rev. D 84, 033005 (2011)]:

$$\Delta\Gamma_s = 0.087 \pm 0.021\ ps^{-1}$$
$$\Phi_s = -0.0363 \pm 0.0013\ rad$$

Exp.	Mode	Dataset	$\phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps^{-1})
CDF	$J/\psi\,\phi$	9.6 fb^{-1}	[−0.60, +0.12], 68% CL	$+0.068 \pm 0.026 \pm 0.009$
D0	$J/\psi\,\phi$	8.0 fb^{-1}	$-0.55^{+0.38}_{-0.36}$	$+0.163^{+0.065}_{-0.064}$
ATLAS	$J/\psi\,\phi$	4.9 fb^{-1}	$+0.12 \pm 0.25 \pm 0.05$	$+0.053 \pm 0.021 \pm 0.010$
ATLAS	$J/\psi\,\phi$	14.3 fb^{-1}	$-0.119 \pm 0.088 \pm 0.036$	$+0.096 \pm 0.013 \pm 0.007$
ATLAS	above 2 combined		$-0.094 \pm 0.083 \pm 0.033$	$+0.082 \pm 0.011 \pm 0.007$
CMS	$J/\psi\,\phi$	20 fb^{-1}	$-0.075 \pm 0.097 \pm 0.031$	$+0.095 \pm 0.013 \pm 0.007$
LHCb	$J/\psi\,K^+K^-$	3.0 fb^{-1}	$-0.058 \pm 0.049 \pm 0.006$	$+0.0805 \pm 0.0091 \pm 0.0033$
LHCb	$J/\psi\,\pi^+\pi^-$	3.0 fb^{-1}	$+0.070 \pm 0.068 \pm 0.008$	—
LHCb	above 2 combined		-0.010 ± 0.039(tot)	—
LHCb	$D_s^+D_s^-$	3.0 fb^{-1}	$+0.02 \pm 0.17 \pm 0.02$	—
All combined			-0.034 ± 0.033	$+0.084 \pm 0.007$

^{p} Preliminary.

Constraints on the CKM Triangle

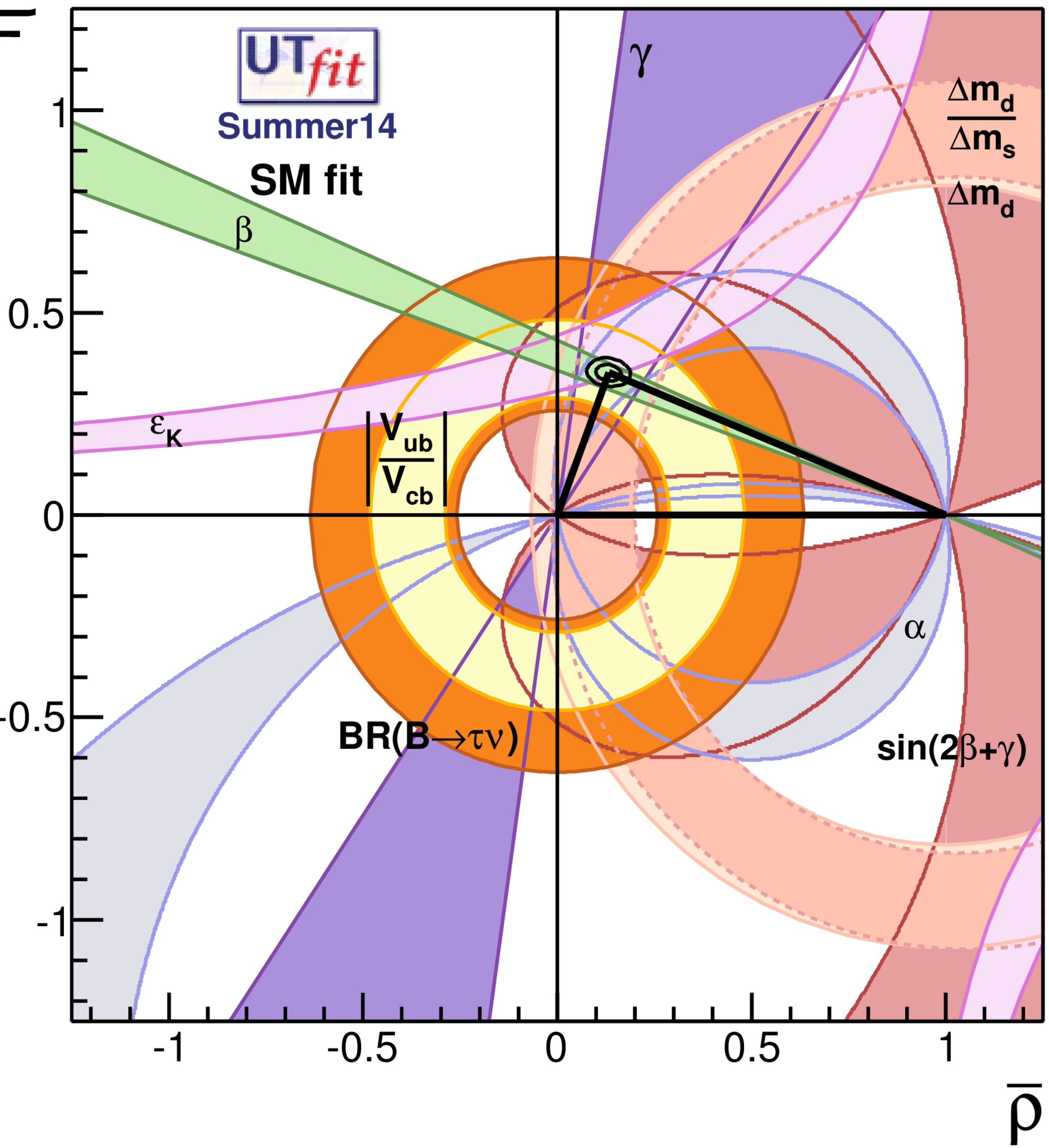
- Various observables related to the CKM matrix elements can be related to fundamental theory parameters.

- Four parameters A, λ, $\bar{\rho}$, $\bar{\eta}$ simultaneously determined by a global fit combining several measurements [Eur. Phys. J. C 41, 1-131 (2005)], [JHEP 0507, 028 (2005)]

- Experimental Inputs:
  - $|V_{ud}|$ (nuclear beta decays, $\pi^+ \rightarrow \pi^0 e^+ \nu$), $|V_{us}|$ (semileptonic K decays)
  - $|V_{cb}|$(semileptonic $b \rightarrow c$ decays), $|V_{ub}|$ (semileptonic $b \rightarrow u$ decays), $|V_{td}|$ (Δm_d), $|V_{ts}|$ (Δm_s)
  - β ($b \rightarrow c\bar{c}s$ decays), α ($b \rightarrow u\bar{u}d$ decays) , γ ($B \rightarrow D^{(*)}K^{(*)}$)
  - $BR(B \rightarrow \tau\nu)$
  - ε_K (CPV in K^0 mixing)
  - m_t, m_b, m_c, m_s, αs, τ_{Bd}, τ_{B+}, τ_{Bs}

- Theoretical Inputs:
  - Connection between quark-level quantities and hadronic-level observables from non-perturative hadronic matrix elements computed using LQCD [Phys. Rev. D 81, 034503 (2010)][

Constraints on the CKM Triangle



Parameter	Output Value	
	CKMfitter	UTfit
$\bar{\rho}$	$0.129^{+0.027}_{-0.022}$	0.130 ± 0.020
$\bar{\eta}$	0.345 ± 0.014	0.348 ± 0.013
$\sin 2\phi_1$	0.684 ± 0.019	0.689 ± 0.018
ϕ_2 [°]	$88.8^{+4.2}_{-3.6}$	88.4 ± 2.8
ϕ_3 [°]	$68.9^{+3.5}_{-4.2}$	69.5 ± 3.0

- Good agreement between different constraints in the global fit

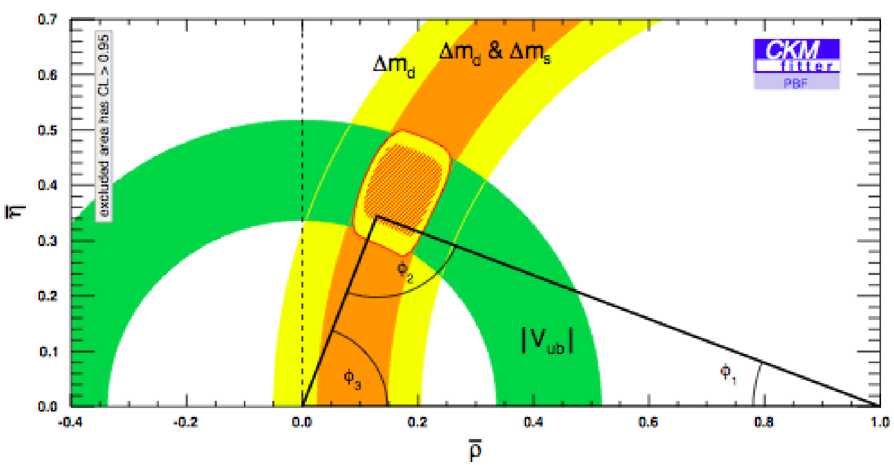
Constraints on the CKM Triangle

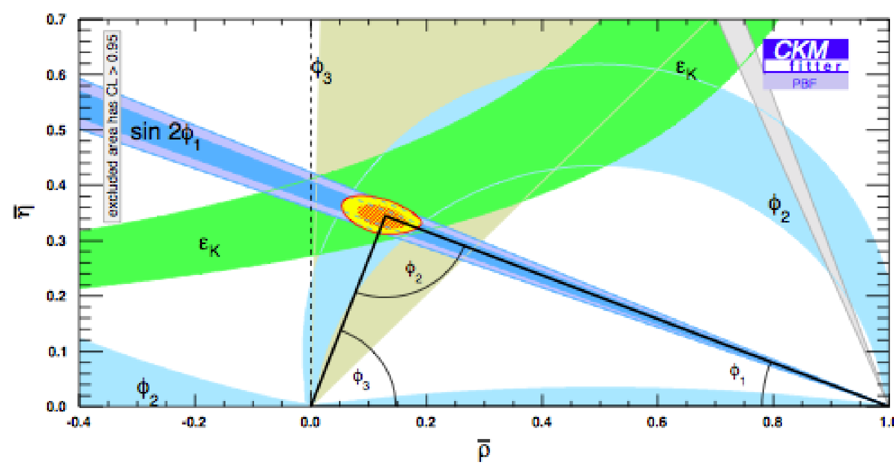
Input	Input value	Predicted value UTfit [#σ]
$\sin 2\phi_1$	0.677 ± 0.020	0.756 ± 0.041 [1.7σ]
ϕ_2 [°]	88 ± 5	88.7 ± 3.3 [0.1σ]
ϕ_3 [°]	67 ± 11	69.7 ± 3.1 [0.2σ]
Δm_s [ps^{-1}]	17.719 ± 0.043	17.35 ± 1.05 [0.7σ]
$\lvert V_{cb}\rvert$ [10^{-3}]	41.67 ± 0.63	42.45 ± 0.65 [0.8σ]
$\lvert V_{ub}\rvert$ [10^{-3}]	3.95 ± 0.54	3.61 ± 0.11 [0.6σ]
$\widehat{B}_K$	$0.7643 \pm 0.0034 \pm 0.0091$	0.810 ± 0.061 [0.3σ]
$\mathcal{B}(B \to \tau\nu_\tau)$ 10^{-4}	(1.15 ± 0.23)	0.818 ± 0.062 [1.4σ]

- Compatibility checked excluding one constraint at a time in the global fit and comparing the fit result with the input
- Maximum discrepancy 1.7 σ statistically compatible

- CP-Conserving observables:
  - Δm_d, Δm_s
  - $|V_{ub}|$

- CP-Violating observables:
  - K observable ε_K
  - Angles from B decays





- Good agreement between the fitted triangle parameters

Constraints on the CKM Triangle

New Physics Constraints from B^0 mixing

- NP can be constrained using the experimental informations on |ΔF|=2 loop-mediated processes

- NP models could introduce several new parameters (flavor changing couplings, short-distance coefficients and matrix elements of new operators)

- Mixing processes depend only on Box Diagrams and can be described in terms of only two parameters which quantify the difference of the amplitute wrt the SM:

$$C_{B_q}\, e^{2i\phi_{B_q}} = \frac{\langle B_q^0 | H_{\rm eff}^{\rm full} | \bar{B}_q^0 \rangle}{\langle B_q^0 | H_{\rm eff}^{\rm SM} | \bar{B}_q^0 \rangle}\,,$$

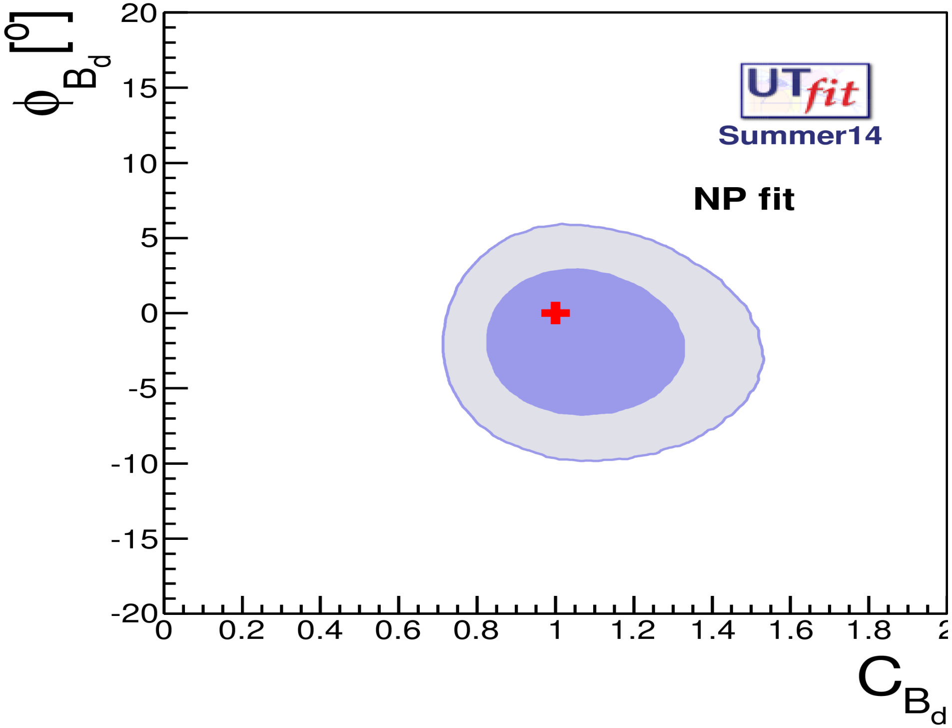
- No NP reflects in C_{bq}=1 & Φ_{Bq}=0

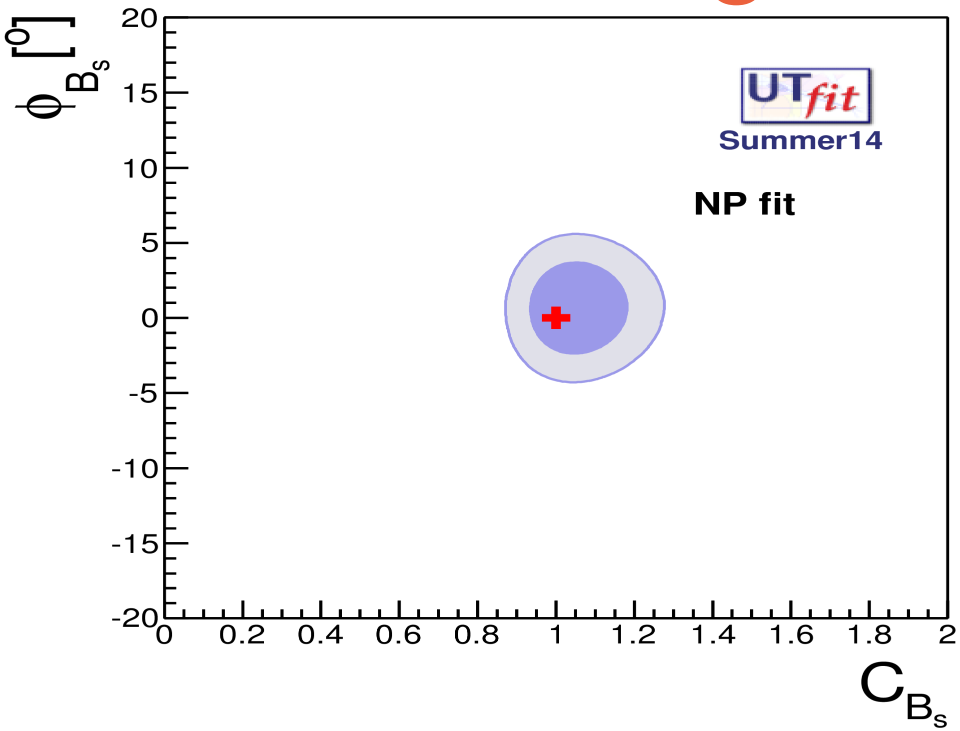
- Relation between observables and NP parameters

$$A_{SL}^{q,\,\exp} = \Im\left(\frac{\Gamma_{12}}{M_{12}}\right)_q = \frac{|\Gamma_{12}^q|}{|M_{12}^q|}\sin\left(\Phi_{12}^{SM} + \Phi_{B_q}^{NP}\right)$$

$$\begin{aligned}
\Delta m_d^{\rm exp} &= C_{B_d} \Delta m_d^{\rm SM}\,,\\
\sin 2\beta^{\rm exp} &= \sin(2\beta^{\rm SM} + 2\phi_{B_d})\,,\\
\alpha^{\rm exp} &= \alpha^{\rm SM} - \phi_{B_d}\,,\\
\Delta m_s^{\rm exp} &= C_{B_s} \Delta m_s^{\rm SM}\,,\\
\phi_s^{\rm exp} &= (\beta_s^{\rm SM} - \phi_{B_s})\,,
\end{aligned}$$

Constraints on the CKM Triangle





Parameter	Input value	Full fit
C_{B_d}	−	1.07 ± 0.17
$\phi_{B_d}[°]$	−	-2.0 ± 3.2
C_{B_s}	−	1.052 ± 0.084
$\phi_{B_s}[°]$	−	0.72 ± 2.06
A_{SL_d}	0.0032 ± 0.0029	-0.0018 ± 0.0017
A_{SL_s}	-0.0047 ± 0.0052	-0.0001 ± 0.00061

- No evidence of NP, but still weak constraints
- Waiting for error reduction

BACKUP

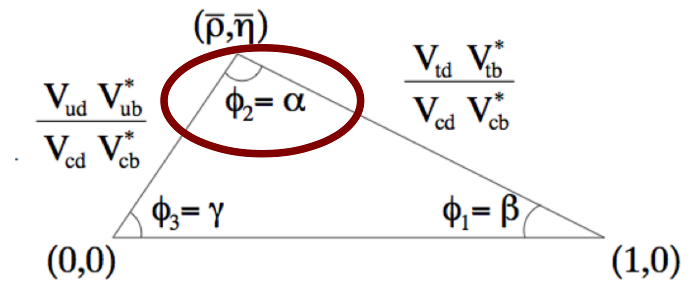
CPV in the Interference: α

$\bar{b} \to \bar{q}q\bar{q}'$	$B^0 \to f$	$B^0_s \to f$	CKM dependence of A_f	Suppression
$\bar{b} \to \bar{u}u\bar{d}$	$\pi^+\pi^-$	$\rho^0 K_S$	$(V^*_{ub}V_{ud})T + (V^*_{tb}V_{td})P^t$	loop

- Suppression ~ 0.2 – 0.3: subleading contribution cannot be neglected:

$$S_{\pi\pi} \approx \sin 2\alpha + 2\,\mathcal{R}e(R_{PT})\cos 2\alpha \sin\alpha\ , \quad C_{\pi\pi} \approx 2\,\mathcal{I}m(R_{PT})\sin\alpha$$

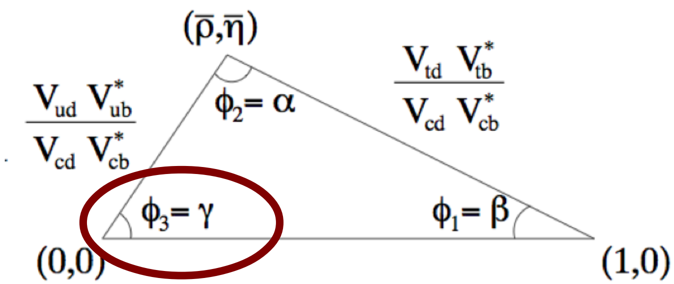
$$R_{PT} \equiv (|V_{tb}V_{td}|\, P^t_{\pi\pi})/(|V_{ub}V_{ud}|\, T_{\pi\pi})$$



- Measurement of the angle $\alpha = arg[-V_{td}V^*_{tb}/V_{ud}V^*_{ub}]$ of the CKM Matrix:
  - R_{PT} model dependent, depends on final state
  - S_f extraction requires knowledge of size and strong phase of penguin contribution (penguin pollution)
  - Strong phase magnitude reflects in C_f size

CPV in the Decay: γ

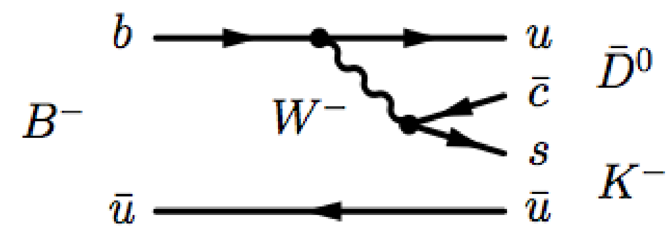
- $B^{\pm} \rightarrow D^{(*)}K^{\pm}$ provide clean determination of CKM angle $\gamma = arg[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}]$



- Use channels with D^0 & $\overline{D}^0$ decays in the same final states

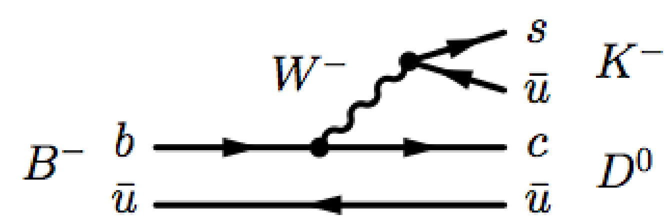
$A_2 \propto V_{ub}V_{cs}^{*}$

CKM & color suppressed



$A_1 \propto V_{cb}V_{us}^{*}$

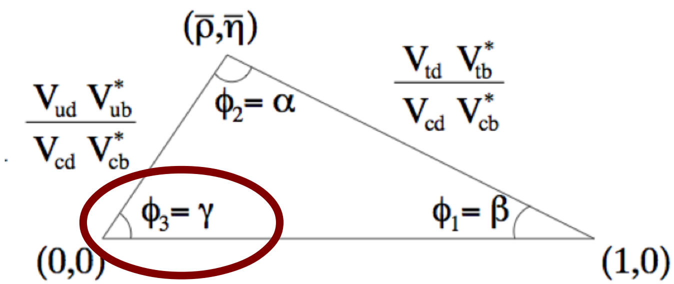
CKM & color allowed



- Accessible through interference of $b \rightarrow u\bar{c}s;\ (B^- \rightarrow \overline{D}^0K^-);\ \overline{D}^0 \rightarrow f$ and $b \rightarrow c\bar{u}s;\ (B^- \rightarrow D^0K^-),\ D^0 \rightarrow f$
- Tree amplitudes with the D^0 and $\overline{D}^0$ decaying to a common final state (e.g. $f = \pi^0 K_S$)
- Theoretically clean since no penguin contributions

CPV in the Decay: γ

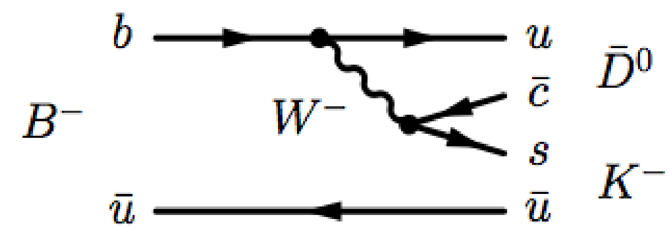
- $B^{\pm} \rightarrow D^{(*)}K^{\pm}$ provide clean determination of CKM angle $\gamma = arg[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}]$



- Use channels with D^0 & $\overline{D}^0$ decays in the same final states

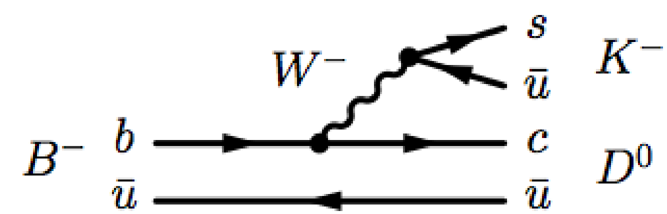
$A_2 \propto V_{ub}V_{cs}^{*}$

CKM & color suppressed



$A_1 \propto V_{cb}V_{us}^{*}$

CKM & color allowed



- Amplitude:

$$|A_{tot}|^2 = |A_1 + A_2|^2 = |A_1|^2 + |A_2|^2 + 2|A_1|^2 r_B \cos(\delta_B + \delta_D - \gamma)$$

where $r_B = \left|\frac{A_2}{A_1}\right| \sim c_f |V_{cs}V_{ub}^{*}/V_{us}V_{cb}^{*}| \sim 0.1,\ \ c_f \sim 0.3 : col.\ \ suppr.\ factor,\ \ \delta_B, \delta_D = strong\ phases$

- If $\gamma \neq 0,\ \ \delta_B + \delta_D \neq 0 \Rightarrow \Gamma(B^{+}) \neq \Gamma(B^{-}) \Rightarrow$ Direct CPV

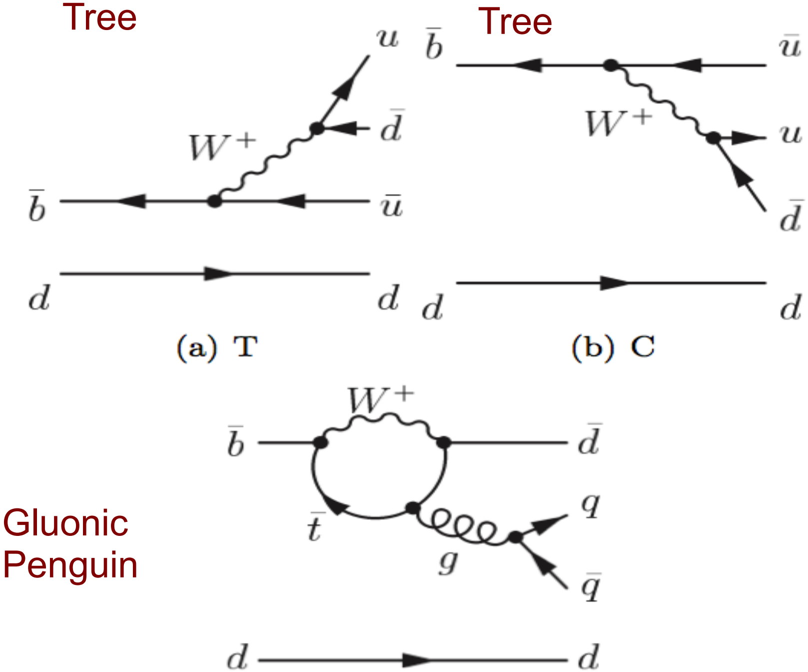
Measurement of α

- CPV from interference between mixing and decay in $b \to u\bar{u}d$ transitions:
  - α measurement from time-dependent asymmetries in $B^0 \to \pi^+\pi^-$ (BR=5×10^{-6})
- Subleading penguin contributions cannot be neglected reflecting in direct CPV and measurement of an effective α^{eff} ($\Delta\alpha = \alpha^{eff} - \alpha$)
- New Physics could enhance penguin: different results using different decay modes
- Additional measurements using Dalitz plot of $B^0 \to \pi^+\pi^-\pi^0$, ρπ, ρρ (VV state requires angular analysis), K* ρ, $a_1\pi$

External Tree

Color suppressed Tree

Gluonic Penguin



(a) T (b) C (c) P

$$\frac{\Gamma(\overline{B} \to \pi^+\pi^-) - \Gamma(B \to \pi^+\pi^-)}{\Gamma(\overline{B} \to \pi^+\pi^-) + \Gamma(B \to \pi^+\pi^-)} = C \cos \Delta m_d \Delta t - S \sin \Delta m_d \Delta t$$

$$C = \frac{1 - |\lambda|^2}{1 + |\lambda|^2};$$

$$S = \frac{2\,\mathrm{Im}\lambda}{1 + |\lambda|^2}$$

$$\lambda = (q/p)\frac{A(\bar{B}^0 \to \pi^+\pi^-)}{A(B^0 \to \pi^+\pi^-)} \neq 1 \quad \to C \neq 0 \quad (Direct\ CPV)$$

Measurement of α

BaBar (467 x 10^6 BB) & Belle (772 x 10^6 BB)

[Phys. Rev. D 87, 052009 (2013), Phys. Rev. D 88, 092003 (2013)]

- $B^0 \rightarrow \pi^+\pi^-$ candidates reconstructed from ΔE & m_{ES} using charged tracks from good quality common vertex
- Dominant BKG from continuum rejected by multivariate discriminants (Fisher) using event shape variables; residual BKG from B → Kπ & higher multiplicity B decays
  - ε_{sig}~90%, ε_{BKG}~35-50%
- Yields and CP parameters from unbineed maximum-likelihood fits to ΔE, m_{ES}, Fisher output, Δt, q (+1: B^0_{tag}, -1: $\overline{B^0}_{tag}$)
- Decay rate PDF:

$$F_q(\Delta t) = \frac{1}{4\tau_{B^0}} e^{-|\Delta t|/\tau_{B^0}} \cdot (1 \ -qC\cos\Delta m_d\Delta t \\ +qS\sin\Delta m_d\Delta t)$$

modified to take into accout Δt resolution and mistag

	$B^0 \rightarrow \pi\pi$	$B^0 \rightarrow K\pi$	$B^0 \rightarrow KK$
Belle	2964±88	9205±124	23±35
BaBar	1394±54	5410±90	7±17

- σΔt~0.7 ps
- Proper time distribution provides further discrimination against continuum (smaller average Δt)

Measurement of α

- Fit Results:

Belle:

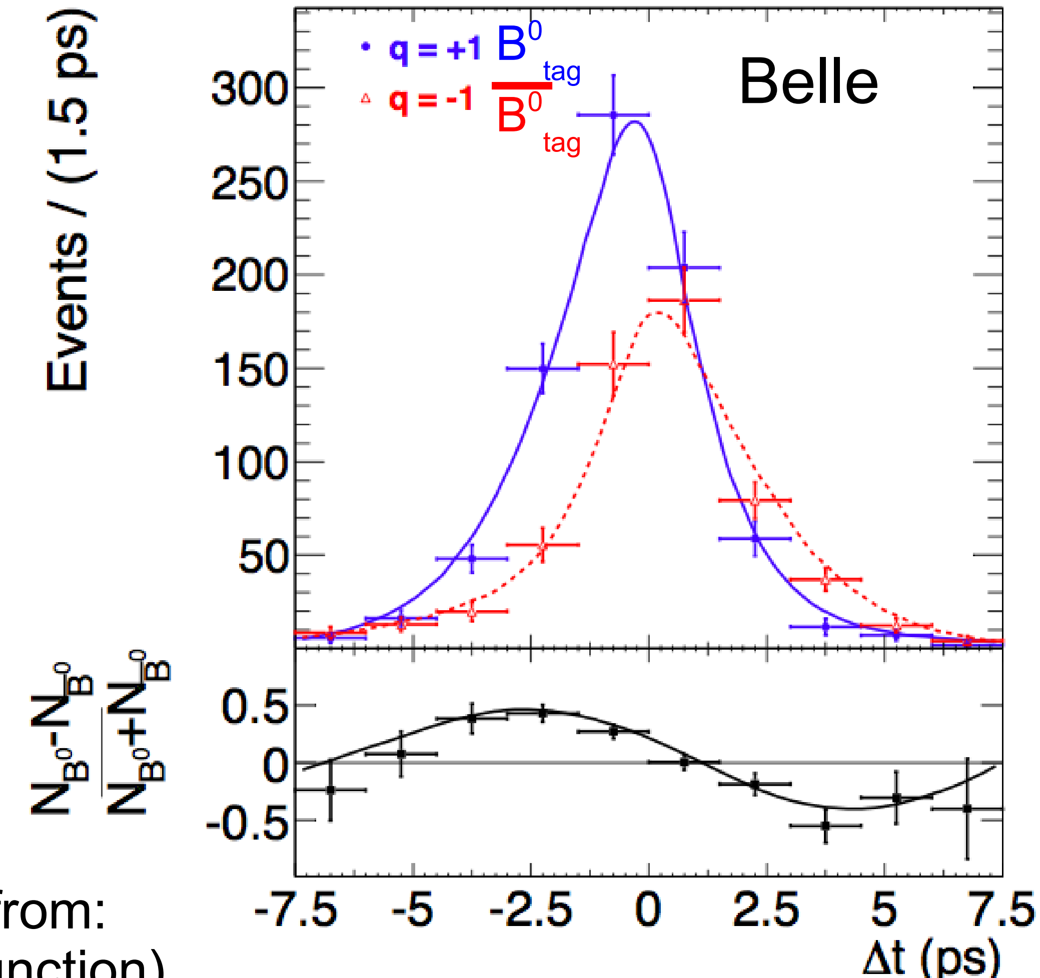
$$S = -0.64 \pm 0.08 \pm 0.03$$
$$C = -0.33 \pm 0.06 \pm 0.03$$

BaBar:

$$S = -0.68 \pm 0.10 \pm 0.03$$
$$C = -0.25 \pm 0.08 \pm 0.02$$

Average:

$$S = -0.66 \pm 0.07$$
$$C = -0.30 \pm 0.05$$



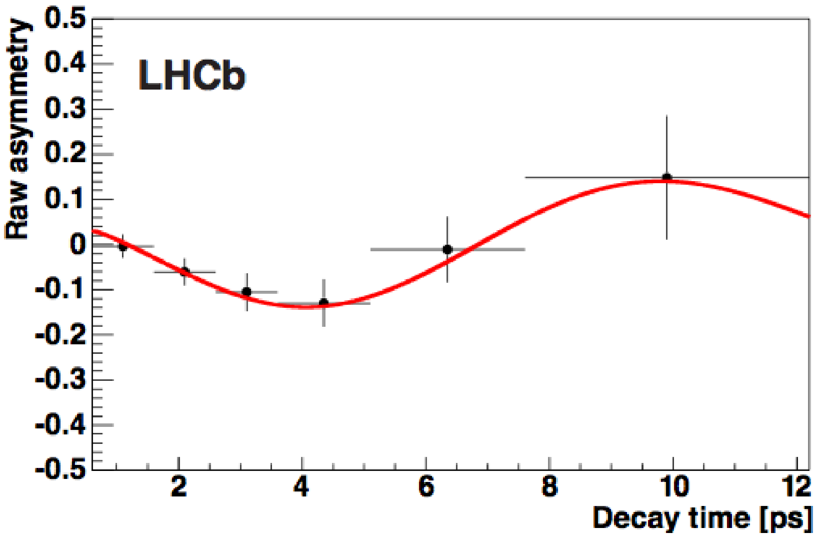
- Systematics (reduced in the asymmetry) from:
  - Δt (detector disalignment, resolution function)
  - Flavor tagging

- Not possible to directly relate the result for S to CKM angle α due to penguin pollution parameterized by $\Delta\alpha = \alpha^{eff} - \alpha$

Measurement of α

LHCb (L=1 fb^{-1}) [JHEP 1310, 183 (2013)]

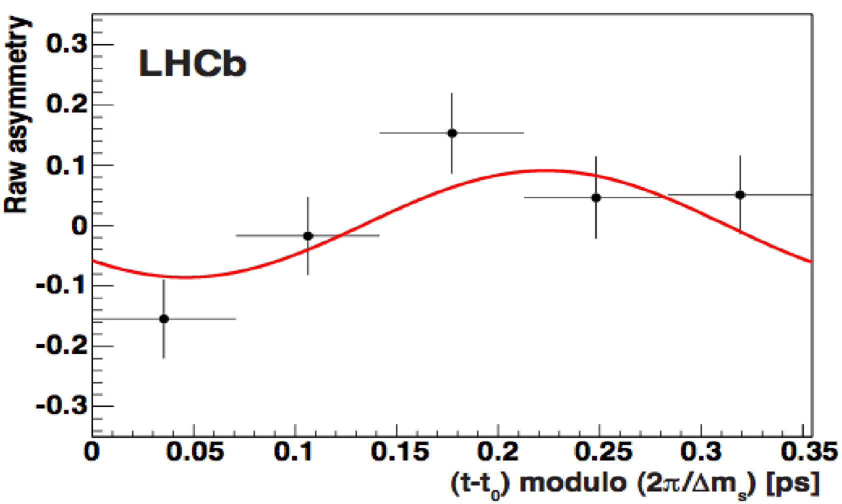
- Using $B \to \pi\pi$



$$S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02$$
$$C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02$$

In agreement with B-Factories

- First measurement of time-dependent direct CPV in $B_s \to KK$



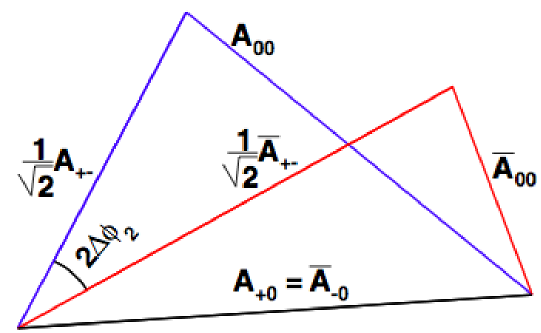
$$S_{KK} = 0.30 \pm 0.12 \pm 0.04$$
$$C_{KK} = 0.14 \pm 0.11 \pm 0.03$$

Measurement of α

- Issue: determine if penguin amplitudes consistent with SM
  - Magnitude and relative phase of the penguin contribution to S determined using isospin relations between the different $B \to \pi\pi$ decay amplitudes

  - $B \to \pi^+\pi^-$ dominated by the external tree (T) & gluonic penguin (P)
  - $B \to \pi^0\pi^0$ dominated by P (internal tree is color suppressed)
  - $B \to \pi^+\pi^0$ pure tree mode (I_3=1 → I=1, 2; I_{gluon}=0 → I_P=0, 1; I=1 forbidden by Bose-Einsten: $I(\pi^+\pi^0)$=2, pure tree)
- Three decay amplitudes $A^{00}(B^0 \to h^0h^0)$, $A^{+-}(B^0 \to h^+h^-)$, $A^{+0}(B^+ \to h^+h^0)$ obey Gronau-London isospin relation [Phys. Rev. Lett. 65, 3381-3384 (1990)]

$$A^{+-}/\sqrt{2} + A^{00} = A^{+0},$$
$$\overline{A}^{+-}/\sqrt{2} + \overline{A}^{00} = \overline{A}^{-0}$$



- Shapes of triangles determined from measurements of BR and CP asymmetries for each of the B → ππ decays

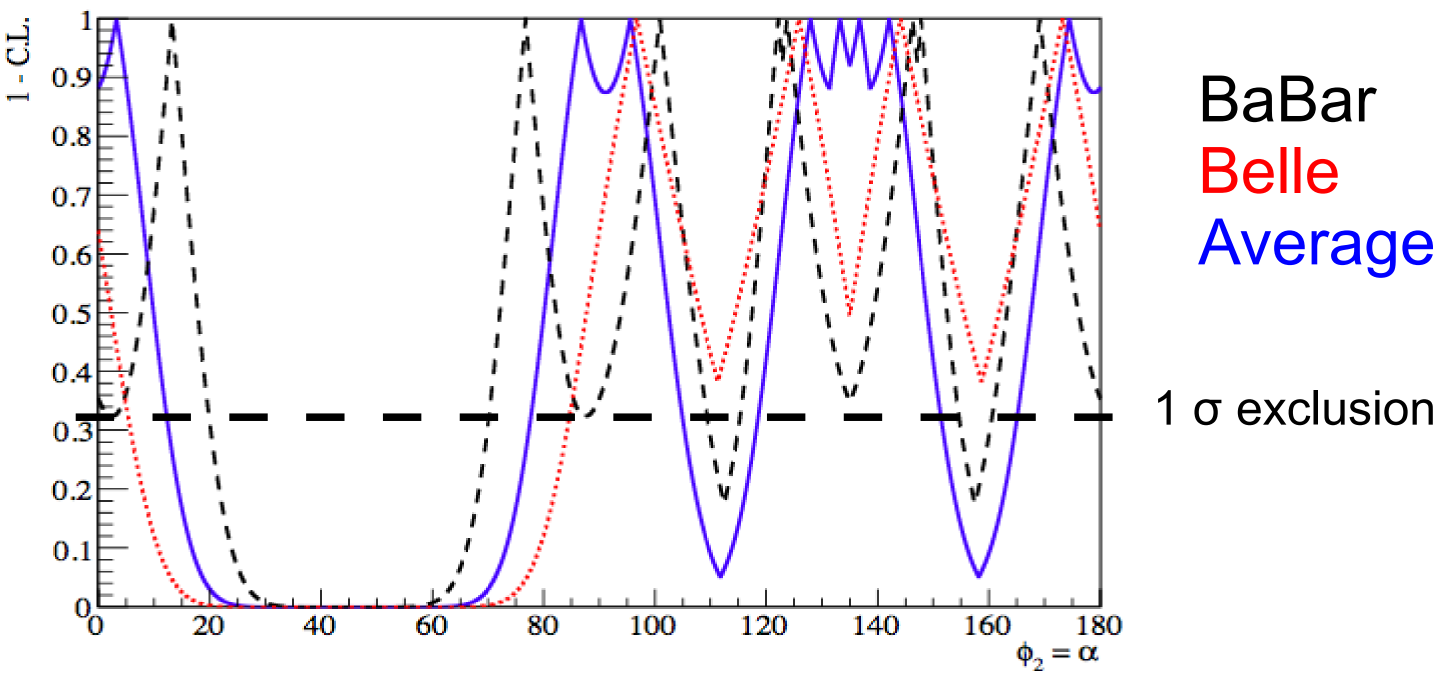
- From the different shapes of the triangles for B and $\overline{B}$, a constraint on $\Delta\alpha = \alpha^{eff} - \alpha$ is obtained

Measurement of α

- Issue: determine if penguin amplitudes consistent with SM
    - SM contribution can be determined using Isospin Analysis

    - Charged mode dominated by the external Tree (T) & gluonic penguin (P)
    - Neutral mode dominated by P (internal tree is color suppressed)

- A χ^2 is constructed for the various amplitudes accounting for the correlations between measured observables in input
- χ^2 is the converted into a p value (CL)

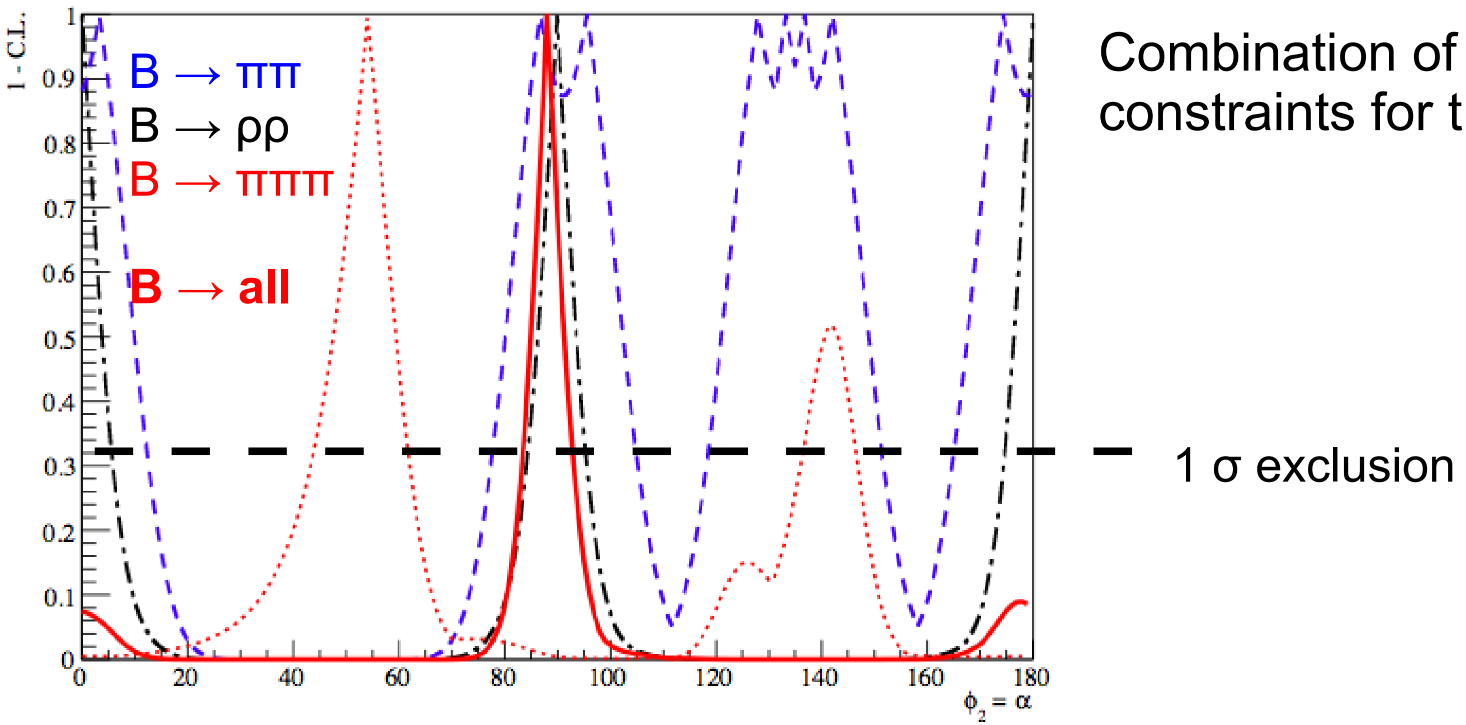


Measurement of α

B-Factories combination

- Constraints on α from different channels give
  $\alpha=(88\pm5)^o$

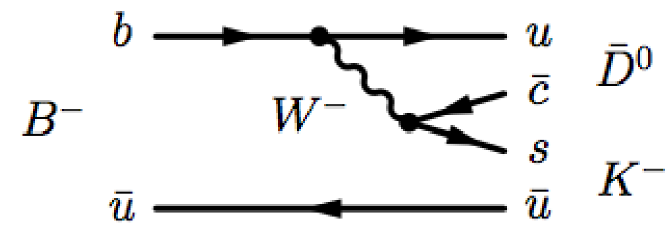
- Dominated by B → ρρ
- B → 3π removes unphysical solution ~0
  - High statistics analysis needed to understand the most probabble value ~ 55°



Combination of the B-Factories constraints for the different channels

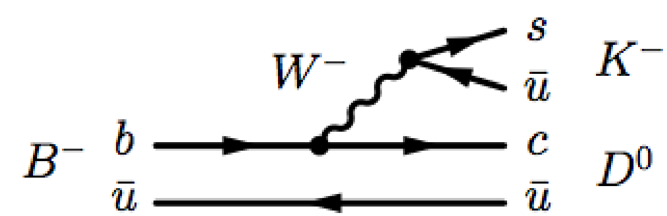
Measurement of γ

- Theoretically clean measurement based on interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ tree amplitudes in the $B^- \to D^{(*)}K^{(*)-}$ decay in same final state



- Hadronic unknowns obtained by experiment:
  r_B: amplitudes ratio, δ_B: relative strong phase

- Several methods available depending on final states:
  - GLW [Phys. Lett. B 253, 483-488 (1991)]:
    Cabibbo-suppressed 2-body CP eigenstates
    $D^0 \to K^+K^-$, $K_s\pi^0$
  - ADS [Phys. Rev. Lett. 78, 3257-3260 (1997)]:
    Cabibbo-favored and doubly Cabibbo-suppressed $D^0 \to K^+\pi^-$ $(K^-\pi^+)$
  - GGSZ [Phys. Rev. D 68, 054018 (2003)]:
    Dalitz-plot of D^0 to 3-body self-conjugate final states $D^0 \to K_s\pi^+\pi^-$
  - Time-dependent decay rates of $B \to D^{-(*)}h^+$ gives $\sin(2\beta+\gamma)$



- Issue: small BRs = $5 \times 10^{-6} - 5 \times 10^{-9}$

Measurement of γ

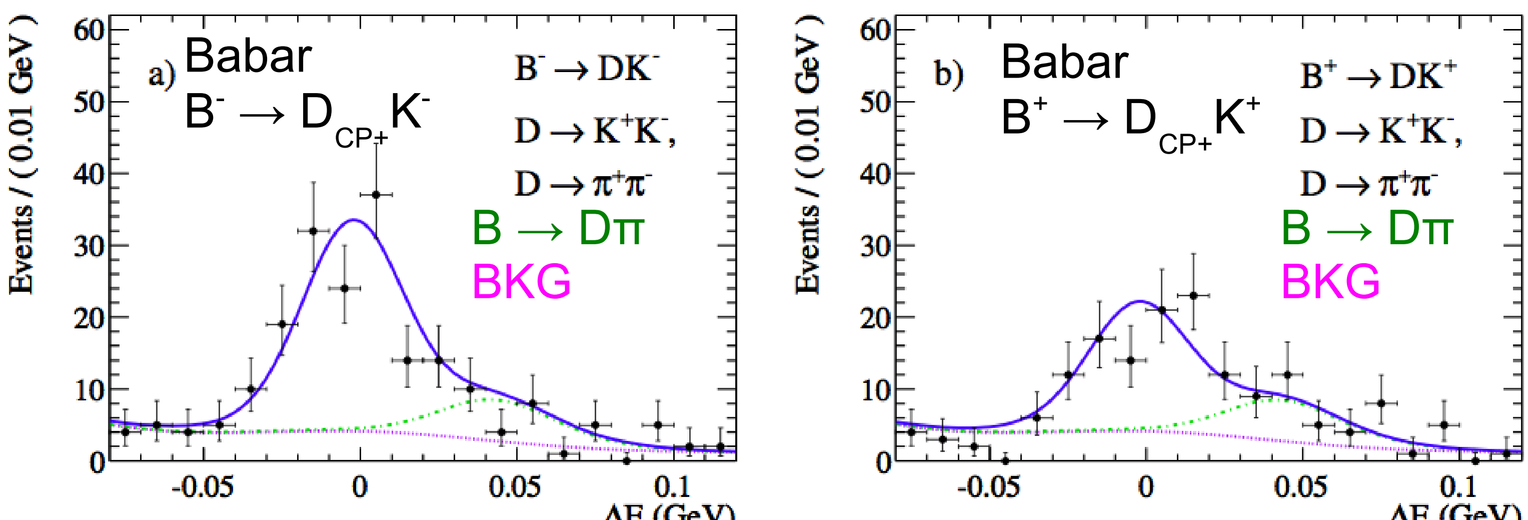
GLW [BaBar, Phys. Rev. D 78, 092002 (2008), Belle, arXiv:1301.2033, LHCb, Phys. Lett. B 712, 203 (2012)]

- D^0 reconstructed in D_{CP+} (K^+K^-, $\pi^+\pi^-$) or D_{CP-} ($K_s\pi^0$, $K_s\omega$, $K_s\Phi$, $K_s\eta$), ($K_S \rightarrow \pi^+\pi^-$, $\pi^0(\eta) \rightarrow \gamma\gamma$)
- Observables (D_{fav}= favored hadronic decay mode as $K^-\pi^+$):

$$R_{CP\pm} = 2\frac{\Gamma(B^-\to D_{CP\pm}K^-)+\Gamma(B^+\to D_{CP\pm}K^+)}{\Gamma(B^-\to D_{fav}K^-)+\Gamma(B^+\to D_{fav}K^+)} = 1 + r_B^2 \pm 2r_B\cos\delta_B\cos\gamma$$

$$A_{CP\pm} = \frac{\Gamma(B^-\to D_{CP\pm}K^-)-\Gamma(B^+\to D_{CP\pm}K^+)}{\Gamma(B^-\to D_{CP\pm}K^-)+\Gamma(B^+\to D_{CP\pm}K^+)} = \pm 2r_B\sin\delta_B\sin\gamma\ /R_{CP\pm}$$

- B candidate fully reconstructed by means of ΔE, m_{ES} optimized to maximize $S/\sqrt{S+B}$
- Continuum BKG suppressed using multivariate discriminants exploiting event shape



Belle+BaBar:

Combined evidence of direct CPV >6σ

Measurement of γ

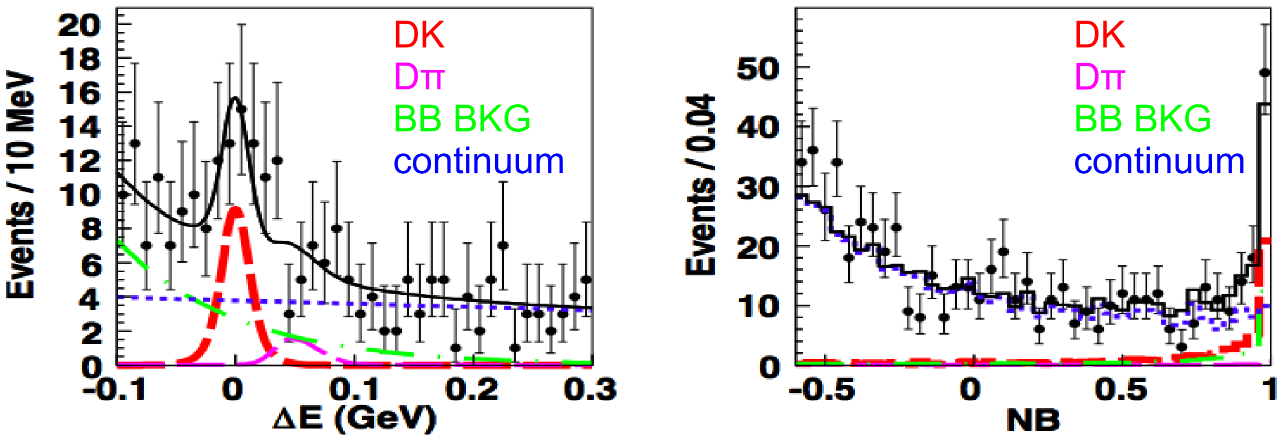
ADS [BaBar, Phys. Rev. D 81, 111103 (2010), Belle, Phys. Rev. Lett. 106 231803 (2011), LHCb, Phys. Lett. B 712, 203 (2012)]

- D^0 decays to non-CP eigenstates via Double Cabibbo-suppressed $D^0 \to K^+\pi^-$ & Cabibbo-favored $\overline{D}^0 \to K^+\pi^-$
- Additional hadronic parameter of the D amplitudes required: r_D: amplitudes ratio, δ_D:relative strong phase (from CLEO-c, BES-III): large effects for $r_B \sim r_D$
- Observables:

$$R_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]K^-) + \Gamma(B^+ \to [K^-\pi^+]K^+)}{\Gamma(B^- \to [K^-\pi^+]K^-) + \Gamma(B^+ \to [K^+\pi^-]K^+)} = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos\gamma$$

$$A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]K^-) - \Gamma(B^+ \to [K^-\pi^+]K^+)}{\Gamma(B^- \to [K^+\pi^-]K^-) + \Gamma(B^+ \to [K^-\pi^+]K^+)} = 2 r_B r_D \sin(\delta_B + \delta_D) \sin\gamma \;/ R_{ADS}$$

- B candidate fully reconstructed (S/N ratio ~$O(10^{-2})$) weaker than GLW)
- Yields extracted from M-L fits to m_{ES} or ΔE and discriminant output



$B^- \to DK^-$, $D \to K^+\pi^-$

- Evidence of CPV ~4σ

Measurement of γ

GGSZ [BaBar, Phys. Rev. D 83, 052001 (2011), Belle, Phys. Rev. D 81, 112002 (2010), LHCb, Phys. Lett. B 718, 43-55 (2012)]

- Measure the phase of the interference between D^0 & $\overline{D^0}$ three body common final states $D \to K_s \pi^+\pi^-$:
  - Large BR=2.83%
  - Significant overlap between D^0 and $\overline{D^0}$ amplitudes → large interference
  - Rich resonant sctructure which results in weak sensitivity to δ_B strong phase
- $B^+ \to DK^+$, $B^- \to DK^-$ amplitudes expressed in terms of D Dalitz-plot variables:

$$A_{B+}(m_+^2, m_-^2) = \overline{A}_D + r_B e^{i(\delta_B+\phi_3)} A_D$$

$$A_{B-}(m_+^2, m_-^2) = A_D + r_B e^{i(\delta_B-\phi_3)} \overline{A}_D$$

$$m_+^2 = m_{K_s\pi^+}^2 \, ; \quad m_-^2 = m_{K_s\pi^-}^2$$

$$A_D = A_D(m_+^2, m_-^2) \qquad D \to K_s \pi^+\pi^-$$

$$\overline{A}_D = \overline{A}_D(m_+^2, m_-^2) \qquad \overline{D} \to K_s \pi^+\pi^-$$

- In case of CP conservation in D^0 decays and neglecting D^0 mixing:

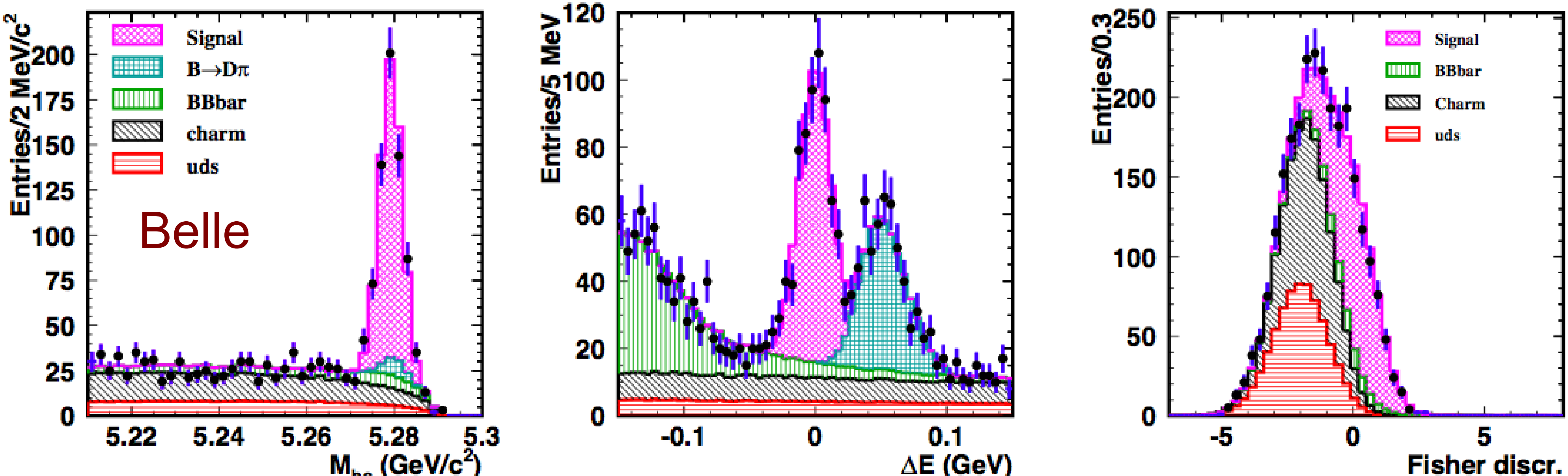
$$\overline{A}_D(m_+^2, m_-^2) = A_D(m_-^2, m_+^2)$$

  - α, δ_B, r_B determined from a fit to the 2-dimensional Dalitz distribution once A_D is known: model required

Measurement of γ

GGSZ [BaBar, Phys. Rev. D 83, 052001 (2011), Belle, Phys. Rev. D 81, 112002 (2010), LHCb, Phys. Lett. B 718, 43-55 (2012)]

- $B \to DK$ selected exploiting m_{ES}, ΔE
  - BKG dominated by continuum suppressed using Fisher discriminant
  - Signal fraction from fit to m_{ES}, ΔE, Fisher, $\cos\theta_{thrust}$

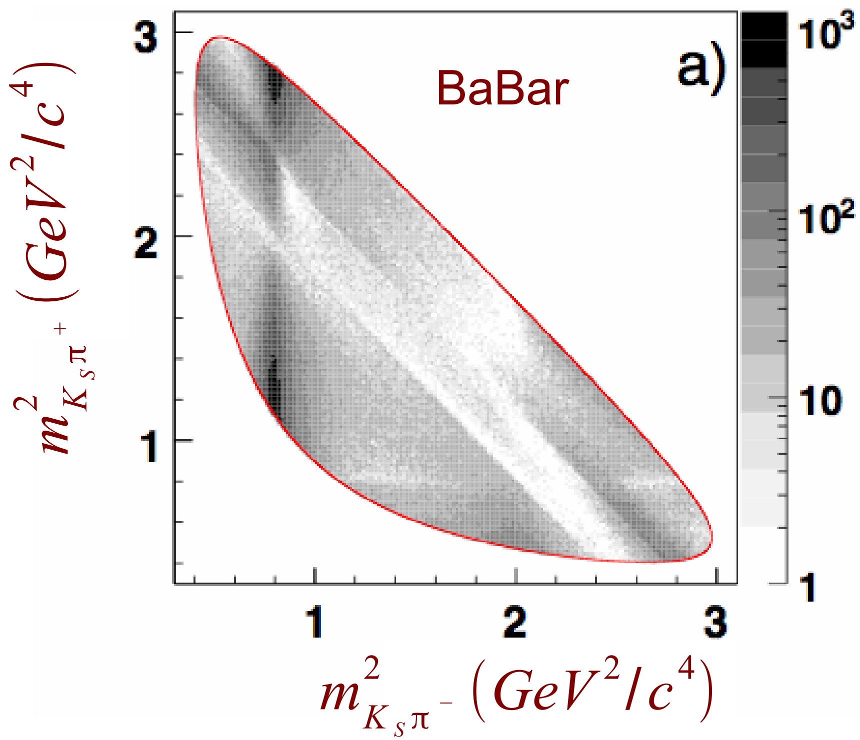


- A_D models:
  - Amplitudes described by relativistic Breit-Wigner S, P and D waves in each of $K_S\pi^+$, $K_S\pi^-$, $\pi^+\pi^-$, flat non-resonant term (isobar model).
  - Used also alternative parameterizations
  - Quality of the amplitude models checked using χ^2 tests

Measurement of γ

GGSZ [BaBar, Phys. Rev. D 83, 052001 (2011), Belle, Phys. Rev. D 81, 112002 (2010), LHCb, Phys. Lett. B 718, 43-55 (2012)]

- Amplitudes and phases from 2D Dalitz-plot fits, Belle:

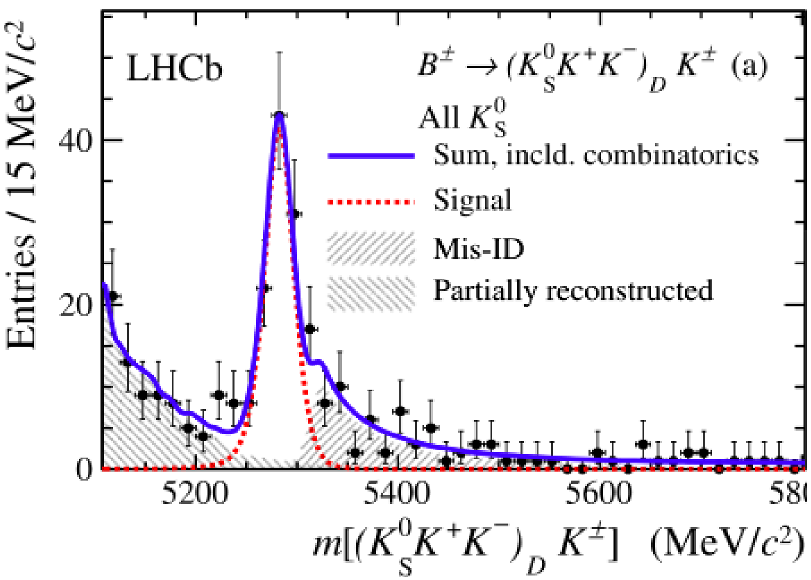


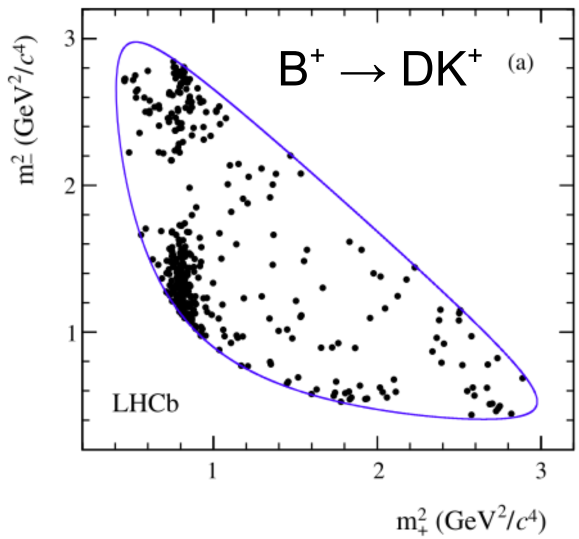
Intermediate state	Amplitude	Phase (°)	Fit fraction (%)
$K_S^0\sigma_1$	1.56 ± 0.06	214 ± 3	11.0 ± 0.7
$K_S^0 f_0(980)$	0.385 ± 0.006	207.3 ± 2.3	4.72 ± 0.05
$K_S^0\sigma_2$	0.20 ± 0.02	212 ± 12	0.54 ± 0.10
$K_S^0 f_0(1370)$	1.56 ± 0.12	110 ± 4	1.9 ± 0.3
$K_S^0\rho(770)^0$	1.0 (fixed)	0 (fixed)	21.2 ± 0.5
$K_S^0\omega(782)$	0.0343 ± 0.0008	112.0 ± 1.3	0.526 ± 0.014
$K_S^0 f_2(1270)$	1.44 ± 0.04	342.9 ± 1.7	1.82 ± 0.05
$K_S^0\rho^0(1450)$	0.49 ± 0.08	64 ± 11	0.11 ± 0.04
$K_0^*(1430)^-\pi^+$	2.21 ± 0.04	358.9 ± 1.1	7.93 ± 0.09
$K_0^*(1430)^+\pi^-$	0.36 ± 0.03	87 ± 4	0.22 ± 0.04
$K^*(892)^-\pi^+$	1.638 ± 0.010	133.2 ± 0.4	62.9 ± 0.8
$K^*(892)^+\pi^-$	0.149 ± 0.004	325.4 ± 1.3	0.526 ± 0.016
$K^*(1410)^-\pi^+$	0.65 ± 0.05	120 ± 4	0.49 ± 0.07
$K^*(1410)^+\pi^-$	0.42 ± 0.04	253 ± 5	0.21 ± 0.03
$K_2^*(1430)^-\pi^+$	0.89 ± 0.03	314.8 ± 1.1	1.40 ± 0.06
$K_2^*(1430)^+\pi^-$	0.23 ± 0.02	275 ± 6	0.093 ± 0.014
$K^*(1680)^-\pi^+$	0.88 ± 0.27	82 ± 17	0.06 ± 0.04
$K^*(1680)^+\pi^-$	2.1 ± 0.2	130 ± 6	0.30 ± 0.07
non-resonant	2.7 ± 0.3	160 ± 5	5.0 ± 1.0

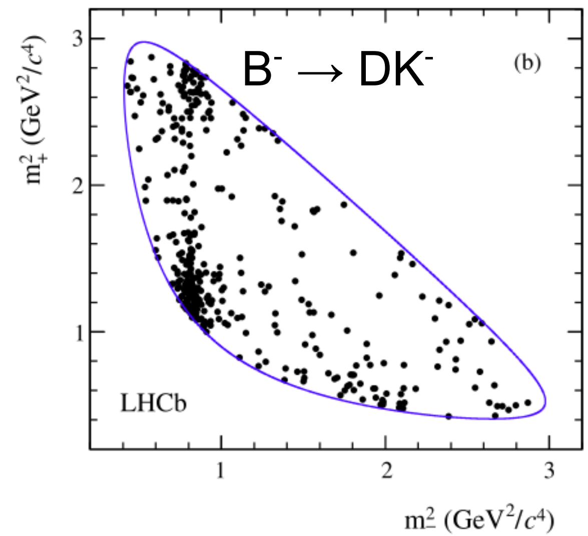
Measurement of γ

GGSZ [Belle, Phys. Rev. D 85, 112014 (2012), LHCb, Phys. Lett. B 718, 43-55 (2012)]

- Dependence on a detailed D amplitude model can be avoided using a binned approach. Amplitude in each bin described by quantities extracted from analyses of charm data → model-independent measurement of γ







$$r_B = 0.07 \pm 0.04\,;\quad \delta_B = \left(137^{+35}_{-46}\right)^o;\quad \gamma = \left(44^{+43}_{-38}\right)^o$$

Measurement of $\Delta\Gamma_d$

- D0 from semileptonic asymmetry measurement (already discussed) [Phys. Rev. D 89 012002 (2014)]:

$$\frac{\Delta\Gamma_d}{\Gamma_d} = (0.50 \pm 1.38) \times 10^{-2}$$

- Summed decay rate of B^0 and $\overline{B}^0$ mesons to a common final state f:

$$\langle \Gamma(B_q^0(t) \to f) \rangle \equiv \Gamma(B_q^0(t) \to f) + \Gamma(\overline{B}_q^0(t) \to f) = R_{q,\mathrm{L}}^f e^{-\Gamma_{q,\mathrm{L}} t} + R_{q,\mathrm{H}}^f e^{-\Gamma_{q,\mathrm{H}} t}$$

  - For non-zero ΔΓ the decay rate is not purely exponential
  - Effective lifetime depending on final state:

$$\tau_{B_q^0 \to f} = \frac{1}{\Gamma_q} \frac{1}{1 - y_q^2} \left(\frac{1 + 2\mathcal{A}_{\Delta\Gamma_q}^f y_q + y_q^2}{1 + \mathcal{A}_{\Delta\Gamma_q}^f y_q} \right)$$

$$\mathcal{A}_{\Delta\Gamma_q}^f \equiv (R_{q,\mathrm{H}}^f - R_{q,\mathrm{L}}^f)/(R_{q,\mathrm{H}}^f + R_{q,\mathrm{L}}^f)$$

$A^{J/\Psi K^*}_{\Delta\Gamma}$=0 (flavor eigenstate)

$A^{J/\Psi KS}_{\Delta\Gamma}$=cos 2β (CP eigenstate)

- LHCb from comparison of the $B^0 \to J/\Psi K^*$ and $B^0 \to J/\Psi K_S$ effective lifetimes [JHEP 04, 114 (2014)]

$$\frac{\Delta\Gamma_d}{\Gamma_d} = -0.044 \pm 0.025 \pm 0.011$$

Measurement of $\Delta\Gamma_d$

- Belle from $B^0 \to J/\Psi K_S$, $J/\Psi K_L$, $D^{(*)-}h^+$, $D^*l\nu$ [Phys. Rev. D 85, 071105 (2012)]
- Using the general time-dependent decay rate allowing for CPT violation (z≠0):

$$B_L = p\sqrt{1-z}\,B^0 + q\sqrt{1+z}\,\bar{B}^0$$
$$B_H = p\sqrt{1+z}\,B^0 - q\sqrt{1-z}\,\bar{B}^0$$

$$\mathcal{P}(\Delta t; f_{\rm rec} f_{\rm tag}) = \frac{\Gamma_d}{2} e^{-\Gamma_d|\Delta t|}\left[\frac{|\eta_+|^2+|\eta_-|^2}{2}\cosh\left(\frac{\Delta\Gamma_d}{2}\Delta t\right) - \mathcal{R}e(\eta_+^*\eta_-)\sinh\left(\frac{\Delta\Gamma_d}{2}\Delta t\right) + \frac{|\eta_+|^2-|\eta_-|^2}{2}\cos(\Delta m_d \Delta t) + \mathcal{I}m(\eta_+^*\eta_-)\sin(\Delta m_d\Delta t)\right],$$

$$\eta_+ \equiv \mathcal{A}_{B^0\to f_{\rm rec}}\mathcal{A}_{\bar{B}^0\to f_{\rm tag}} - \mathcal{A}_{\bar{B}^0\to f_{\rm rec}}\mathcal{A}_{B^0\to f_{\rm tag}},$$
$$\eta_- \equiv \sqrt{1-z^2}\left(\frac{p}{q}\mathcal{A}_{B^0\to f_{\rm rec}}\mathcal{A}_{B^0\to f_{\rm tag}} - \frac{q}{p}\mathcal{A}_{\bar{B}^0\to f_{\rm rec}}\mathcal{A}_{\bar{B}^0\to f_{\rm tag}}\right) + z\left(\mathcal{A}_{B^0\to f_{\rm rec}}\mathcal{A}_{\bar{B}^0\to f_{\rm tag}} + \mathcal{A}_{\bar{B}^0\to f_{\rm rec}}\mathcal{A}_{B^0\to f_{\rm tag}}\right)$$

$$\Re z = [1.9 \pm 3.7 \pm 3.3]\,10^{-2}$$
$$\Im(z) = -5.7 \pm 3.3 \pm 3.3\,10^{-3}$$
$$\frac{\Delta\Gamma_d}{\Gamma_d} = [-1.7 \pm 1.8 \pm 1.1]\,10^{-2}$$

World Average: $\frac{\Delta\Gamma_d}{\Gamma_d} = 0.001 \pm 0.010$