Resolving The Sign Ambiguity in $\Delta\Gamma_s$

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Based on:

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Plan of Talk

- Introduction and Motivation
- Resolving the sign ambiguity with $B_s \to D_s K$
- Concluding remarks

B physics: Mixing and decay

- Apart from the direct search of BSM physics at colliders low energy observables in flavor physics plays an important role for an indirect search of NP
- NP in B: look in CP asymmetries, branching fractions, mass and lifetime differences
- FCNC processes play an important role for the detection of NP effects
- It is obvious that $B_s - \overline{B_s}$ mixing will play an important role in the search for NP in $b \to s$ FCNC processes

ΔM_q and $\Delta\Gamma_q$

Basic definition

Effective Hamiltonian for $B_q - \bar{B}_q$ mixing

$$H_{eff} = \begin{pmatrix} M_{11q} - \frac{i}{2}\Gamma_{11q} & M_{12q} - \frac{i}{2}\Gamma_{12q} \\ M^*_{12q} - \frac{i}{2}\Gamma^*_{12q} & M_{11q} - \frac{i}{2}\Gamma_{11q} \end{pmatrix}$$

Mass eigenstates

$|B_L\rangle = p|B_q\rangle + q|\bar{B}_q\rangle$

$|B_H\rangle = p|B_q\rangle - q|\bar{B}_q\rangle$

Eigenvalues $\mu_{L,H} = M_{L,H} - \frac{i}{2}\Gamma_{L,H}$

$M_{L,H} \Longrightarrow$ Masses of $B_{L,H}$, $\Gamma_{L,H} \Longrightarrow$ Decay widths of $B_{L,H}$

In general $M_H > M_L$ And within SM $\Gamma_L > \Gamma_H$

Basic definition

Oscillation frequency : $\Delta M_s = M_{H s} - M_{L s} = 2|M_{12s}|$
Width difference : $\Delta\Gamma_s = \Gamma_{L s} - \Gamma_{H s} = \frac{4Re(M_{12s}\Gamma^*_{12s})}{\Delta M_s}$
$= 2|\Gamma_{12s}| \cos\phi_s$

These quantities are defined from:

$\phi_s = arg\left(-\frac{M^s_{12}}{\Gamma^s_{12}}\right) = \phi_s^{SM} + \phi_s^{\Delta} - 2\beta_s$ with $\phi_s^{SM} = 0.24^\circ \pm 0.08^\circ$

and β_s is the phase from $b \to c\bar{c}s$ decay amplitude

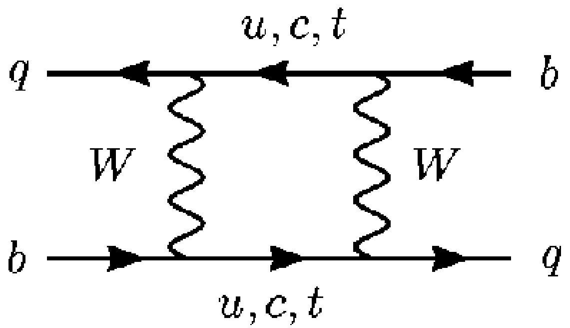
$2M_{Bq}\langle B^0_q|H^{\Delta B=2}_{eff}|\bar{B}^0_q\rangle = M_{12q} - \frac{i}{2}\Gamma_{12q}$

- Mass difference can be calculated from the dispersive part of the box diagram
- Width difference can be calculated from the absorptive part of the box diagram

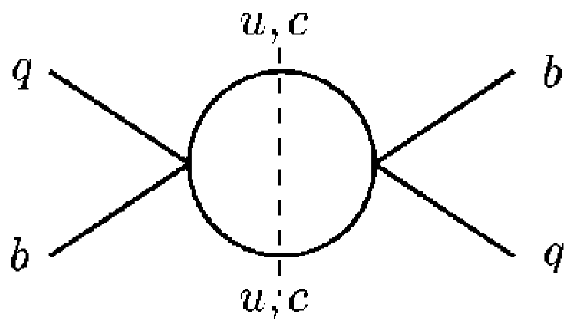
Basic definition

- Only the box diagrams with internal c and u quarks contribute to decay width difference
- For B_s systems the intermediate $c\bar{c}$ contribution is the dominating one
- Decay width for B_d system have contributions from intermediate $c\bar{c}$,$u\bar{u}$,$u\bar{c}$ and $c\bar{u}$ box diagrams

$M_{12} \sim$



$\Gamma_{12} \sim$



Importance of measurement of $\Delta\Gamma_s$

- $\Delta\Gamma_s$ is positive in SM $\Rightarrow \Gamma_L > \Gamma_H$
  $\Rightarrow$ A negative sign of $\Delta\Gamma_s$ will be a clear signal of NP
- Sign of $\cos\phi_s^\Delta$ will determine the sign of $\Delta\Gamma_s$
  ($\Delta\Gamma_s = 2|\Gamma_s^{12}|\cos\phi_s^\Delta$)
- CDF has measured
  $\phi_s^\Delta - 2\beta_s \in [-1.36, -0.24] \cup [-2.90, -1.78]$ at 68% CL
- $\Delta\Gamma_s/\Gamma_s$ is expected to be large, $(15 \pm 6)\%$ [SM], is large enough to be accessible by experiment in near future
- If this is outside the SM range, NP!!

Sign ambiguities in $\Delta\Gamma_s$

- The lifetime measurement in an untagged decay to a *CP* eigenstate determine $\Gamma_s^{12}\cos(\phi_s^\Delta - 2\beta_s)\cos(\phi_s^\Delta + \phi_{SM})$
  $\longrightarrow$ determines ϕ_s^Δ with four-fold ambiguity
  $\phi_s^\Delta \leftrightarrow \pi \pm \phi_s^\Delta$
  $\phi_s^\Delta \leftrightarrow -\phi_s^\Delta - \phi_s^{SM} + 2\beta_s^{SM}$
  $\phi_s^\Delta \leftrightarrow -\phi_s^\Delta - \phi_s^{SM} + 2\beta_s^{SM} + \pi$
- Constrain on ϕ_s^Δ from the *CP* asymmetry ($a_{fs}^s \propto \sin(\phi_s^\Delta + \phi_s^{SM})$) measurement of untagged flavour specific B_s decays, has a two-fold ambiguity ($\phi_s^\Delta \leftrightarrow \pi - \phi_s^\Delta$)

How to resolve this ambiguity?

It is possible to resolve it with $B_s \to D_s K$

$$\lambda_{D_s^- K^+} = \frac{q}{p} \frac{\langle D_s^- K^+ | \overline{B}_s \rangle}{\langle D_s^- K^+ | B_s \rangle} = |\lambda_{D_s^- K^+}| e^{-i\,(\gamma_s + \phi_s^\Delta - \delta)}$$

$$\lambda_{D_s^+ K^-} = \frac{q}{p} \frac{\langle D_s^+ K^- | \overline{B}_s \rangle}{\langle D_s^+ K^- | B_s \rangle} = \frac{1}{|\lambda_{D_s^- K^+}|} e^{-i\,(\gamma_s + \phi_s^\Delta + \delta)}$$

Tagged $B_s \to D_s^\pm K^\mp$ decay will determine $\phi_s^\Delta - 2\beta_s + \gamma$

Time dependent decay rate

$$\Gamma\left(B_s(t) \longrightarrow D_s^{\mp} K^{\pm}\right)$$
$$= N e^{-\Gamma_s t}\Big[\cosh(\tfrac{\Delta\Gamma_s\, t}{2}) \pm \left(1 - b\,|\lambda_{D_s^- K^+}|\right) \cos(\Delta M_s\, t)$$
$$- b\,\cos(\gamma_s + \phi_s^{\Delta} \mp \delta)\sinh(\tfrac{\Delta\Gamma_s\, t}{2}) + b\,\sin(\gamma_s + \phi_s^{\Delta} \mp \delta)\sin(\Delta M_s\, t)\Big]$$

$$\Gamma\left(\overline{B}_s(t) \longrightarrow D_s^{\mp} K^{\pm}\right)$$
$$= N e^{-\Gamma_s t}\Big[\cosh(\tfrac{\Delta\Gamma_s\, t}{2}) \mp \left(1 - b\,|\lambda_{D_s^- K^+}|\right) \cos(\Delta M_s\, t)$$
$$- b\,\cos(\gamma_s + \phi_s^{\Delta} \mp \delta)\sinh(\tfrac{\Delta\Gamma_s\, t}{2}) - b\,\sin(\gamma_s + \phi_s^{\Delta} \mp \delta)\sin(\Delta M_s\, t)\Big]$$

with, $b = \frac{2\,|\lambda_{D_s^- K^+}|}{1+|\lambda_{D_s^- K^+}|^2}$

Untagged analysis

Untagged decay rate

$$\Gamma\left[D_s^{\mp}K^{\pm},t\right] \equiv \Gamma\left(B_s(t)\to D_s^{\mp}K^{\pm}\right) + \Gamma\left(\bar{B}_s(t)\to D_s^{\mp}K^{\pm}\right)$$
$$= 2Ne^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - b\cos(\gamma_s + \phi_s^{\Delta} \mp \delta)\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right]$$

- We can determine branching fraction and lifetime from the untagged decay rate
- The overall normalization constant is related to *CP*-averaged branching fraction

Branching fractions

$$\mathcal{B}(B_s^0 \to D_s^{\mp} K^{\pm}) = \frac{N}{\Gamma_s}\left[1 - b\cos(\gamma_s - \phi_s^{\Delta} \mp \delta)\frac{\Delta\Gamma_s}{\Gamma_s}\right]$$

Branching ratios will not be useful to remove the sign ambiguity

Ratio of branching fractions:

$$\frac{\mathcal{B}(B_s \to D_s^+ K^-) - \mathcal{B}(B_s \to D_s^- K^+)}{\mathcal{B}(B_s \to D_s^+ K^-) + \mathcal{B}(B_s \to D_s^- K^+)} = b\frac{\sin(\gamma_s + \phi_s^{\Delta})\sin\delta}{1 - \cos(\gamma_s + \phi_s^{\Delta})\cos\delta}\frac{\Delta\Gamma_s}{2\Gamma_s}$$

The ratio of branching fractions will be useful to place tighter bound on $|\sin(\gamma_s + \phi_s^{\Delta})\sin\delta|$

Lifetime informations

Maximum likelihood fit of untagged decay rate to a single exponential $\propto exp^{[} - \Gamma_{D_s^{\mp} K^{\pm}} t]$ determines

$$\Gamma_{D_s^{\mp} K^{\pm}} = \Gamma_s + b \cos(\gamma_s + \phi_s^{\Delta} \mp \delta) \, \frac{\Delta\Gamma_s}{2}$$

$$\Gamma_s + b \cos(\gamma_s + \phi_s^{\Delta} \mp \delta) \cos \phi_s^{\Delta} |\Gamma_{12}^s|$$

After addition: $\frac{\Gamma_{D_s^+ K^-} + \Gamma_{D_s^- K^+}}{2} - \Gamma_s$

$$= b \cos \delta \cos(\gamma_s + \phi_s^{\Delta}) \cos \phi_s^{\Delta} \; |\Gamma_{12}^s| \equiv L \; |\Gamma_{12}^s|$$

Inputs

- We assume the fact that γ is well known from the B-factories $\rightarrow$ Measured *CP* asymmetries in $B_d \rightarrow \rho^+\rho^-$ and $B_d \rightarrow J/\psi K_s$ are combined to solve : $\gamma = \pi - \alpha - \beta = 71^\circ \pm 5^\circ$
- $\beta_s = arg[V_{ts}V_{tb}^*/V_{cs}V_{cb}^*] = 1.1^\circ \pm 0.3^\circ$
- We use the realistic value for $|\lambda_{D_s^- K^+}| \approx 0.4$
- We have taken the strong phase $|\delta| < 0.2$

L vs $\sin(\phi_s^\Delta - 2\beta_s)$

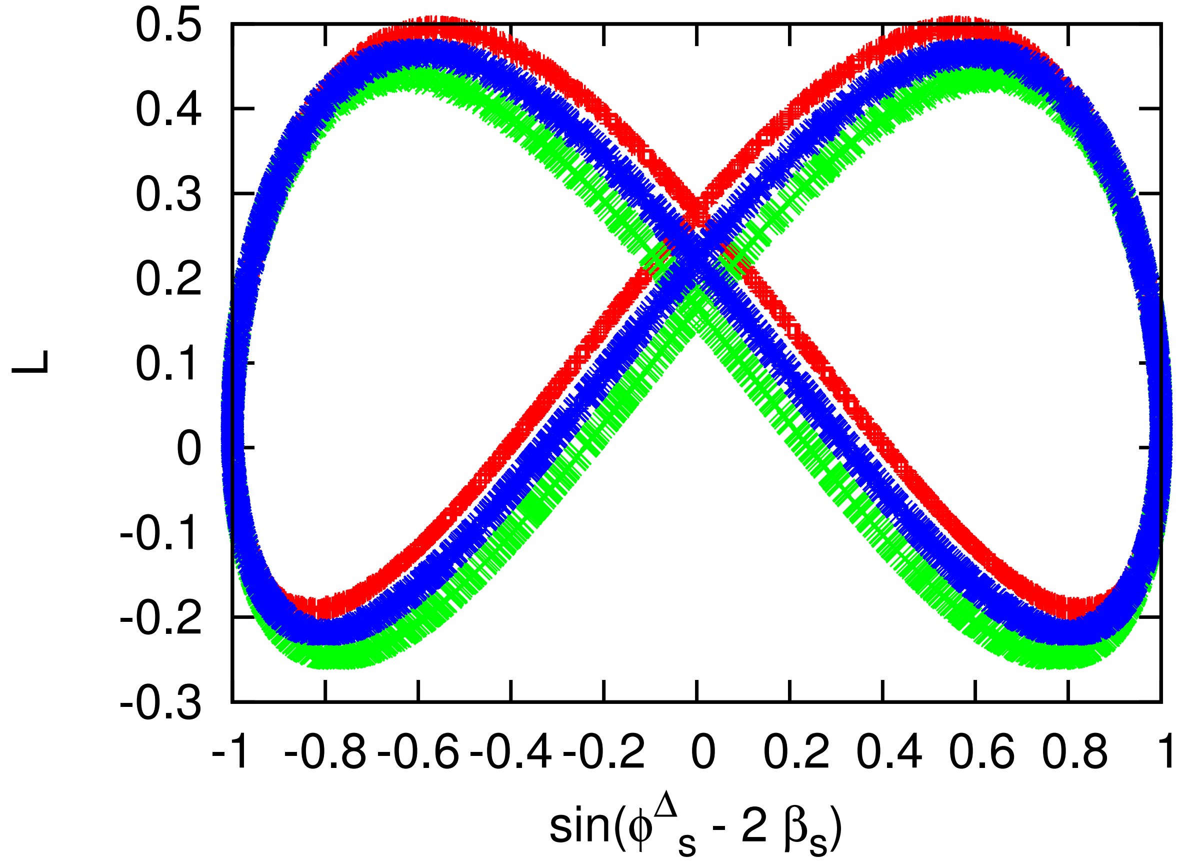


Figure 1: For $\sin(\phi_s^\Delta - 2\beta_s) = -0.72$, $L > 0 \rightarrow \Delta\Gamma_s > 0$ and $L < 0 \rightarrow \Delta\Gamma_s < 0$

Tagged analysis

With :

$$\Gamma(B_s(t) \to D_s K) = [\Gamma(B_s(t) \to D_s^- K^+) + \Gamma(B_s(t) \to D_s^+ K^-)]/2$$

The *CP* asymmetry can be defined as :

$$\frac{\Gamma(B_s(t)\to D_s K)-\Gamma(\overline{B}_s(t)\to D_s K)}{\Gamma(B_s(t)\to D_s K)+\Gamma(\overline{B}_s(t)\to D_s K)} = \frac{b\cos\delta\sin(\gamma_s+\phi_s^\Delta)\sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s/2) - b\cos\delta\cos(\gamma_s+\phi_s^\Delta)\sinh(\Delta\Gamma_s/2)}$$

The coefficient of the oscillating term:

$S \equiv b\cos\delta\sin(\gamma_s + \phi_s^\Delta) \to$ This term will be useful to remove the discrete ambiguity $\phi_s^\Delta \leftrightarrow \pi - \phi_s^\Delta + 2\beta_s$

S vs $\sin(\phi_s^\Delta - 2\beta_s)$

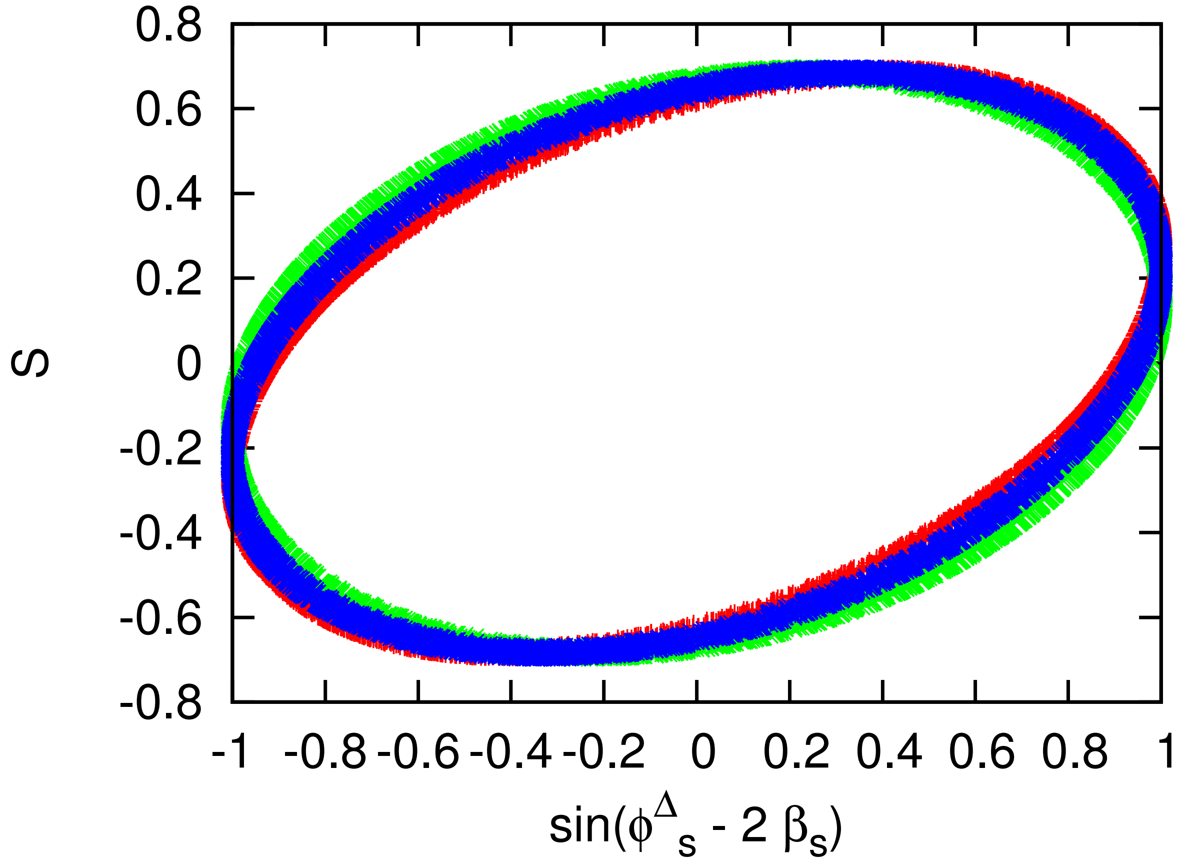


Figure 2: Two solutions with $\sin(\phi_s^\Delta - 2\beta_s) = -0.72$
$\rightarrow S \approx 0.3 and S \approx -0.6$

Tagged + Untagged

What we will get if we combine tagged and untagged analysis?

Combining tagged and untagged analysis we can define :

$\tan(\gamma_s + \phi_s^{\Delta}) = \frac{S}{L} \cos \phi_s^{\Delta}$

- Using above equation we can resolve the ambiguity even if we don't have any knowledge about δ
- Above equation has four solutions for ϕ_s^{Δ} $\longrightarrow$ Two of them can be eliminated with the information on the sign of "S"
- Remaining two solutions are not related by $\phi_s^{\Delta} - 2\beta_s \leftrightarrow \pi - \phi_s^{\Delta} + 2\beta_s$

Conclusions

- It is important to determine the sign of $\Delta\Gamma_s \rightarrow$ negative $\Delta\Gamma_s$ will be a clear signal for New Physics
- In combination with $B_s \rightarrow J/\psi\phi$, the discrete ambiguity can be resolved from tagged and untagged analysis of $B_s \rightarrow D_s K$
- Lifetime measurement with an accuracy of roughly 2% requiring at least 2500 events
- Tagged measurement looks better $\Rightarrow$ a fairly small data sample should permit to discriminate between the two solutions