# $B_s - \bar{B}_s$ mixing, lifetime difference $\Delta\Gamma_s$ and the Physics Beyond Standard Model

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# Plan of Talk

- $\Delta\Gamma_s$ and $\Delta M_s$: SM and NP
- Sign ambiguities in $\Delta\Gamma_s$: Resolution
- New Physics in $\Delta\Gamma_s$: Implication for Large Dimuon Asymmetry ?
- Concluding remarks

# B physics: Mixing and decay

- Low energy observables in flavor physics play 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
- Data from $K$, $D$ and $B_d$ mesons have been consistent with SM picture $\Rightarrow$ Most of the anomalous results have been found in $b \to s$ transitions $\Rightarrow$ $B_s$ meson, interesting and important portal for indirect detection of NP

# 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 $\Gamma_L > \Gamma_H$

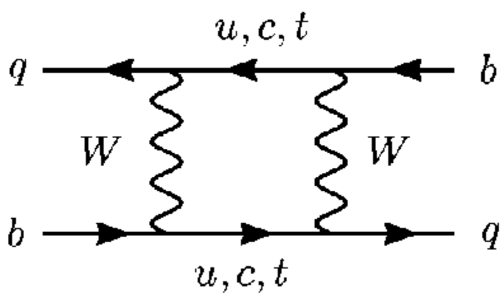
# Basic definition

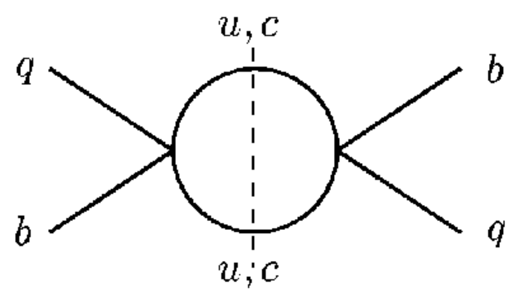
Oscillation frequency : $\Delta M_s = M_{H_s} - M_{L_s} = 2|M_{12s}|$

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 $\beta_s$ is the phase from decay amplitude

$M_{12} \sim$ 


$\Gamma_{12} \sim$ 

# Quantities of interest

Quantities of particular interest:

- $\Delta M_s \Rightarrow$ Mass difference
- $\Delta \Gamma_s \Rightarrow$ Decay width difference
- $a_{fs} \Rightarrow$ CP asymmetry for flavor specific decay $(B \to f)$
- $A^b_{sl} \Rightarrow$ Recently observed dimuon asymmetry

$a_{fs} = \frac{|\Gamma_{12s}|}{|M_{12s}|} \sin\phi_s$

$A^b_{sl} = (0.506 \pm 0.043)\, a^d_{sl} \;+\; (0.494 \pm 0.043)\, a^s_{sl}$

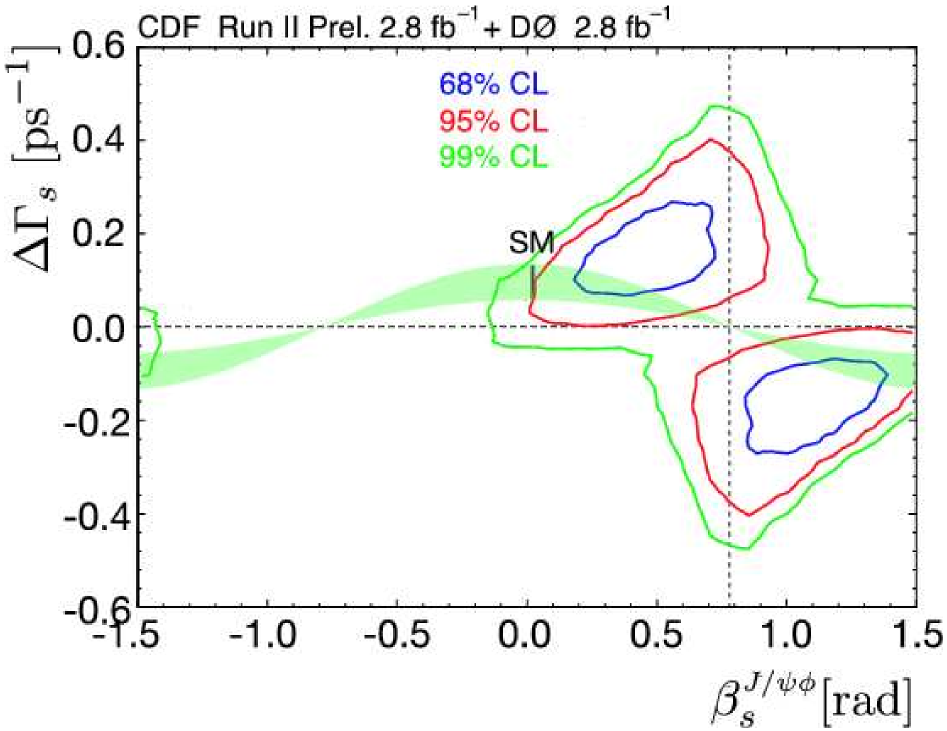
$\Rightarrow$ SM prediction $\mathcal{O}(10^{-4})$ Lenz & Nierste [hep-ph/0612167]

$\Rightarrow -0.00957 \pm 0.00251\,(stat) \pm 0.00146\,(syst)$

DØ collaboration, [arxiv:1005.2757]

# CP asymmetry in $B_s \to J/\psi\phi$

$\beta_s^{J/\psi\phi} = -\frac{1}{2}(\phi_s^\Delta - 2\beta_s^{SM}) \in [0.27, 0.59] \cup [0.97, 1.30]$ at 68% CL




⇒ CDF update with $5.2\ fb^{-1}$ data $\in [0.0, 0.5] \cup [1.1, 1.5]$ at 68% CL [Talk by Oakes, FPCP 2010]

⇒ Sign of $\cos(\phi_s^\Delta - 2\beta_s)$ determines the sign of $\Delta\Gamma_s$ ($\Delta\Gamma_s = 2|\Gamma_s^{12}|\cos(\phi_s^\Delta - 2\beta_s)$)

⇒ $\Delta\Gamma_s$, with negative sign will be a clear signal of NP

# Resolution

Resolving the sign ambiguity through $B_s \to D_s K$ SN & U. Nierste [arXiv:0801.0143]

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

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

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

# Untagged decay rate

$$\Gamma\left[D_s^{\mp}K^{\pm},t\right] \equiv \Gamma\left(B_s(t)\to D_s^{\mp}K^{\pm}\right)+\Gamma\left(\bar{B}_s(t)\to D_s^{\mp}K^{\pm}\right)$$
$$= 2Ne^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - b\cos(\gamma_s+\phi_s^{\Delta}\mp\delta)\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right]$$
$$\Rightarrow b = 2\frac{|\lambda_{D_s^- K^+}|}{1+|\lambda_{D_s^- K^+}|^2}$$

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

# Lifetime informations

SN & U. Nierste [arXiv:0801.0143]

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

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

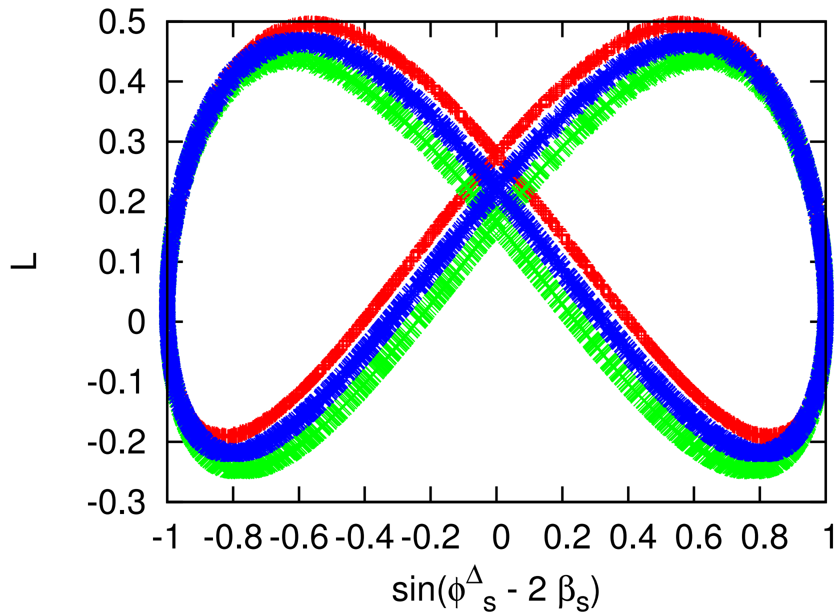
$$= b\cos\delta\cos(\gamma_s + \phi_s^\Delta)\cos\phi_s^\Delta\ |\Gamma_{12}^s| \equiv L\ |\Gamma_{12}^s|$$

# L vs $\sin(\phi_s^\Delta - 2\beta_s^{SM})$

SN & U. Nierste [arXiv:0801.0143]

$\gamma = 71° \pm 5°$ from $B \to \pi\pi, \rho\pi, \rho\rho$ M. Beneke [hep-ph/0612353]

$|\delta| < 0.2, \quad |\lambda_{D_s^- K^+}| \approx 0.4$




For negative $\sin(\phi_s^\Delta - 2\beta_s^{SM}) \Rightarrow L > 0 \to \Delta\Gamma_s > 0$ and $L < 0 \to \Delta\Gamma_s < 0$

# Tagged analysis

SN & U. Nierste [arXiv:0801.0143]

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 :

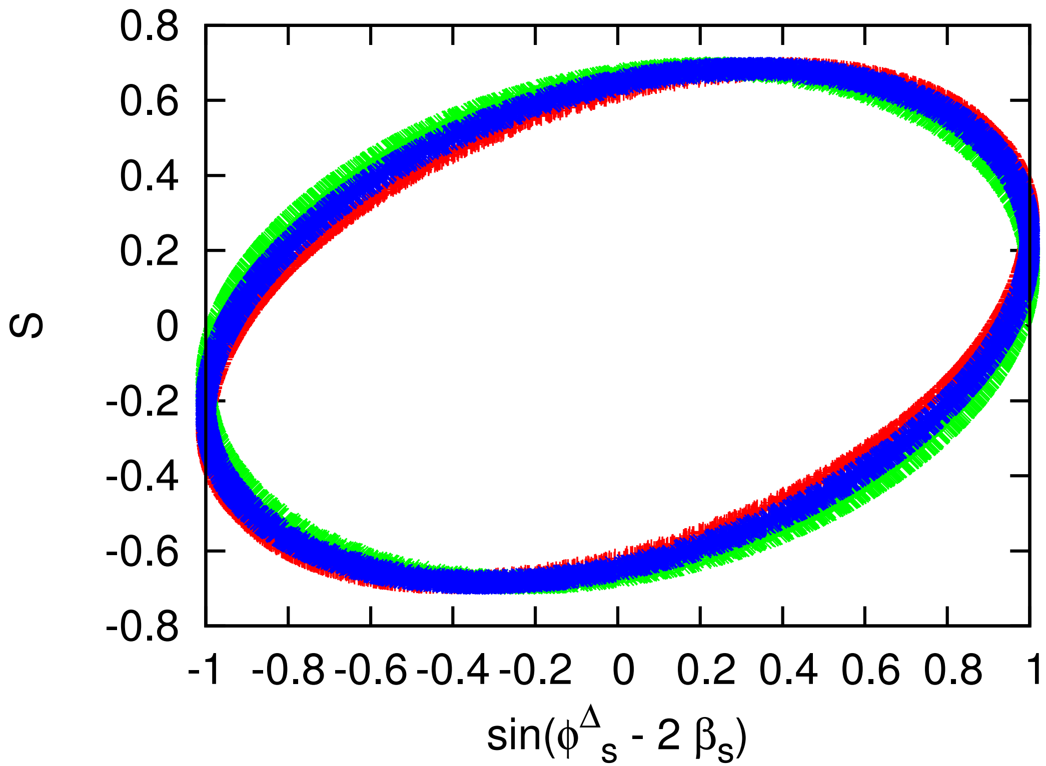
$$\frac{\Gamma(B_s(t)\to D_s K) - \Gamma(\overline{B}_s(t)\to D_s K)}{\Gamma(B_s(t)\to D_s K) + \Gamma(\overline{B}_s(t)\to D_s K)} = \frac{b\cos\delta\sin(\gamma_s+\phi_s^\Delta)\sin(\Delta M_s t)}{\cosh(\Delta\Gamma_s/2) - b\cos\delta\cos(\gamma_s+\phi_s^\Delta)\sinh(\Delta\Gamma_s/2)}$$

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 $\phi_s^\Delta \leftrightarrow \pi - \phi_s^\Delta$

# S vs $\sin(\phi_s^\Delta - 2\beta_s^{SM})$

SN & U. Nierste [arXiv:0801.0143]




⇒ Two solutions can be discriminated even if New Phase is close to zero

⇒ Upper region and lower region corresponds to $\Delta\Gamma_s > 0$ and $\Delta\Gamma_s < 0$ respectively

# 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 $\delta$
- Above equation has four solutions for $\phi_s^{\Delta} \rightarrow$ Two of them can be eliminated with the information on the sign of "S"
- Remaining two solutions are not related by $\phi_s^{\Delta} - 2\beta_s \leftrightarrow \pi - \phi_s^{\Delta} + 2\beta_s$

# New Physics and $\Gamma_{12}^s$

Folklore: NP contributes to mixing, not to decay    Grossman [hep-ph/9603244]

If NP affects significantly to mixing but not to decay the likely results are the enhancement of $\Delta M_s$ and a suppression of $\Delta\Gamma_s = \Delta\Gamma_{SM}^s \cos\phi_s^\Delta \Rightarrow$ If $\phi_s^\Delta$ is different from zero $\cos\phi_s^\Delta < 1 \Rightarrow$ As a result $\Delta\Gamma_s < \Delta\Gamma_{SM}^s$

Suppose both $M_{12}^s$ and $\Gamma_{12}^s$ are affected (examples later)

$$\Delta\Gamma_s = |\Gamma_{12}^s| \cos(\phi_s^\Delta - 2\beta_s^{NP}), \qquad a_{fs} = \frac{\Delta\Gamma_s}{\Delta M_s} \tan(\phi_s^\Delta - 2\beta_s^{NP})$$

- $\Delta\Gamma_s \leq \Delta\Gamma_s^{SM}$ is not necessarily true, it may even larger than the SM value
- Phase in $\Delta\Gamma_s$ is now the relative phase between mixing and decay $\Rightarrow$ Phase extracted from semileptonic asymmetry measurement should not be taken as the phase measured from $B_s \to J/\psi\phi$

# BSM physics and $\Gamma_{12}^s$

NP effects only mixing when there are no light d.o.f. in the box diagram $\Rightarrow$ True for most of the minimal flavour violation type model

Exceptions: Models where the box diagram contains two light degrees of freedom $\Rightarrow$ results in an absorptive part
$\Rightarrow$ contributes to $\Gamma_{12}^s$

Few Examples: (i) Leptoquark, (ii) R-parity violating SUSY A. Dighe, A. Kundu and SN [arXiv:0705.4547 & 1005.4051]

- These models can have flavour dependent couplings of two light SM particles with one heavy BSM particle $\Rightarrow$ contribute to $\Gamma_{12}^s$
- Leptoquarks are more interesting, as the corresponding bounds are weaker, so large effect in $\Delta\Gamma_s$

# Leptoquark

A. Dighe, A. Kundu and SN [arXiv:0705.4547 & 1005.4051]

- Leptoquarks are colour-triplet objects that couples to quarks and leptons
- Leptoquarks that couple to neutrinos are tightly constrained from neutrino mass and oscillation data, should not have large contribution
- We restrict ourselves to scalar leptoquark $S_0$ (can be extended to vector leptoquark) with couplings of the form: $\lambda_{ij} \bar{d}^c_{jR} e_{iR} S_0^\dagger + h.c \Rightarrow$ (i,j=1,2,3),
- We chose $\lambda_{32}$ and $\lambda_{33}$ to be non-zero $\Rightarrow$ It generates an effective four-fermion $(S+P)\times(S+P)$ interaction leading to $b \to s\tau^+\tau^-$ $\Rightarrow$ Contribute to $B_s - \bar{B}_s$ mixing, $\Delta\Gamma_s$, leptonic decay $B_s \to \tau^+\tau^-$ and to semileptonic decay $B_s \to X_s\tau^+\tau^-$

# Recent measurements and $\Delta\Gamma_s$

Hint of NP effect in $\Gamma_{12}^s$, in the light of recent measurements at Tevatron:

Like sign dimuon asymmetry in the $B$ system $A_{sl}^b$,

$\Rightarrow (8.0 \pm 9.0 \pm 6.8) \times 10^{-3}$ CDF collaboration, 1.6 $fb^{-1}$ of data [note 9015, Oct. 2007]

$\Rightarrow (-9.57 \pm 2.51 \pm 1.46) \times 10^{-3}$ DØ collaboration, 6.1 $fb^{-1}$ of data [arxiv: 1005.2757]

$\Rightarrow$ Combining these results, one finds $A_{sl}^b = -(8.5 \pm 2.8) \times 10^{-3} \Rightarrow$ 3$\sigma$ away from SM prediction

$\Rightarrow$ From above results one finds semileptonic asymmetry, $(a_{sl}^s)_{a_{sl}^d meas} = -(9.2 \pm 4.9) \times 10^{-3}$

Other Inputs: $\Delta M_s = (17.78 \pm 0.12)\, ps^{-1}$, $\Delta\Gamma_s = (0.154^{+0.054}_{-0.070})\, ps^{-1}$, $\sin\phi_s^{\Delta} = 0.69^{+0.16}_{0.23}$

$\Rightarrow$ Good Fit Result: $|\Gamma_{12}^s| = (0.112 \pm 0.040)\, ps^{-1}$ Ligeti et.al. [arxiv:1006.0432]

C. Bauer & N. Dunn [arxiv:1006.1629]

$\Rightarrow$ SM prediction $|\Gamma_{12}^s|^{SM} = (0.049 \pm 0.012)\, ps^{-1}$ (1.5$\sigma$ dev.) Lenz & Nierste [hep-ph/0612167]

Indication from life time ratio,

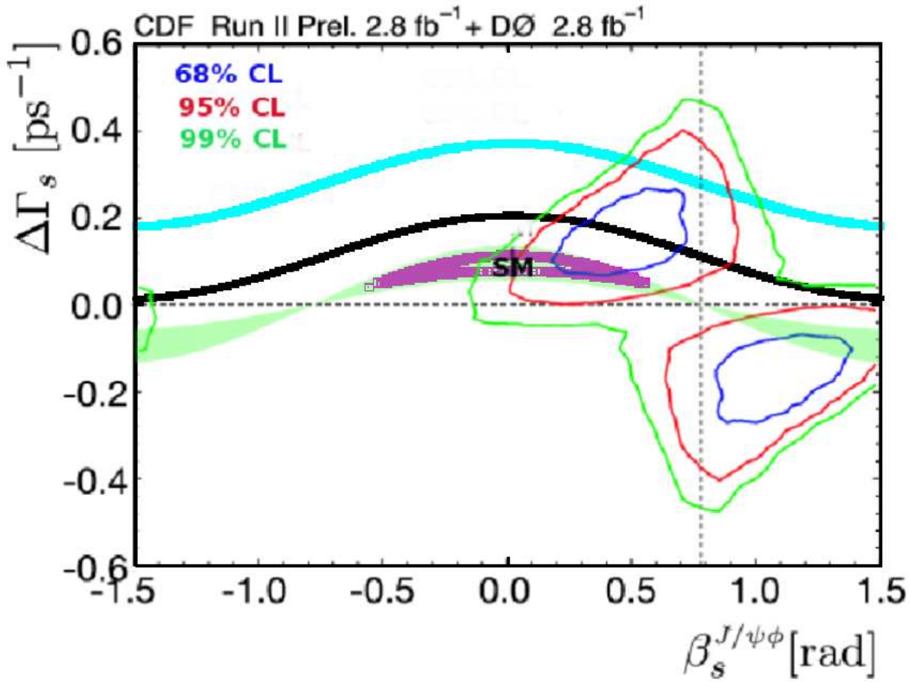
$\Rightarrow \left(\frac{\tau(B_s)}{\tau(B_d)}\right)_{SM} = 1 \pm \mathcal{O}(1\%)$ Neubert & Sachrajda [hep-ph/9603202]

$\Rightarrow \left(\frac{\tau(B_s)}{\tau(B_d)}\right)_{EXP} = 0.965 \pm 0.017 \Rightarrow$ Indicate a $2\sigma$ dev. HFAG

# $\Delta\Gamma_s$ vs CP phase in $B_s \to J/\psi\phi$

A. Dighe, A. Kundu and SN [arxiv:1005.4051]

Correlation for three different values of $Br(B_s \to \tau^+\tau^-)$

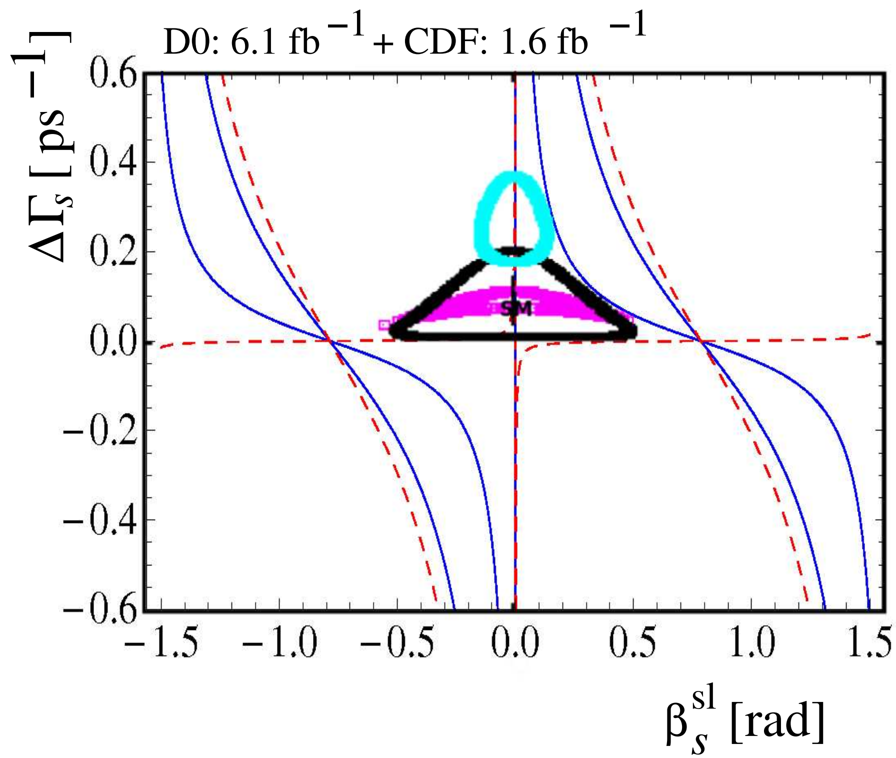



$\Rightarrow$ Allow us to be within the 68% CL $\Rightarrow$ Additional leptoquark can enhance $\Delta\Gamma_s$ and $\beta^{J/\psi\phi}$ $\Rightarrow$

correlated with an enhancement in $Br(B_s \to \tau^+\tau^-)$

# $\Delta\Gamma_s$ vs phase from $a^s_{fs}$

A. Dighe, A. Kundu and SN [arXiv:1005.4051]




$\Rightarrow A^b_{sl} = (0.506 \pm 0.043)\, a^d_{sl} + (0.494 \pm 0.043)\, a^s_{sl}, \quad a^s_{sl} = \frac{\Delta\Gamma_s}{\Delta M_s} \tan(\phi^\Delta_s - \beta^{NP}_s)$

$\Rightarrow$ An enhancement in $\Delta\Gamma_s$ can also explain large dimuon asymmetry

# 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
- The enhancement of $\Delta\Gamma_s$ is correlated with an enhancement of $BR(B_s \rightarrow \tau^+\tau^-) \Rightarrow$ looking for $\tau$ pairs in Belle and LHC-B has great importance $\Rightarrow$ Alternatively precise measurement of the lifetime ratio $\frac{\tau(B_s)}{\tau(B_d)}$ is also useful to understand the NP effects in $\Gamma^s_{12}$

Thank you !

# 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 $\phi_s^{\Delta}$ 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 $\phi_s^{\Delta}$ 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

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

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

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

# 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 $|\sin(\gamma_s + \phi_s^{\Delta})\sin\delta|$