# $A^s_{SL}$ and $\Delta\Gamma_s$ at Tevatron and Beyond

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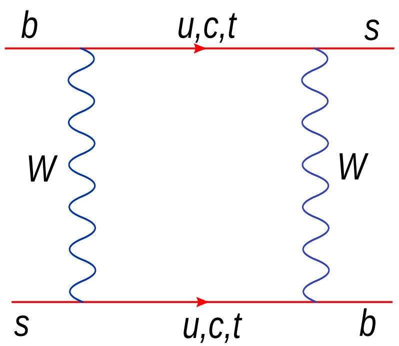
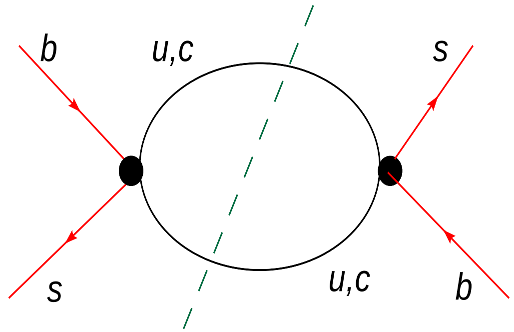
# $B_s$ system: Properties and observables

- Within SM, $B_s$-$\bar{B}_s$ mixing proceeds via box diagram: dispersive part leads to $M_{12}^s$ ($\Delta m_s$) and absorptive part to $\Gamma_{12}^s$ ($\Delta\Gamma_s$) [$|B_{L,H}\rangle = p|B_s\rangle \pm q|\bar{B}_s\rangle$]




- Define the following phases: $\phi_M = \arg(M_{12}^s)$ $\quad \phi_s = \phi_M - \arg(-\Gamma_{12}^s)$

Within SM, $\Gamma_{12}^s$ is dominated by $b \to c\bar{c}s$ with $\arg(-\Gamma_{12}) = \arg(V_{cb}V_{cs}^*)^2 \sim \arg(V_{tb}V_{ts}^*)^2$ leading to: $\quad \phi_M^{SM} = \arg(V_{tb}V_{ts}^*)^2 \sim -1^\circ \quad \phi_s^{SM} \sim 0$

- $\Delta m_s = 2|M_{12}^s| \quad \Delta\Gamma_s = 2|\Gamma_{12}^s|\cos\phi_s \quad \frac{q}{p} = -e^{-i\phi_M}(1 - \frac{1}{2}\underbrace{|\frac{\Gamma_{12}^s}{M_{12}^s}|\sin\phi_s}_{a_{fs}})$

- Within SM, $\quad \Delta\Gamma_s^{SM} = \Delta\Gamma_s^{CP} \quad (= 2|\Gamma_{12}^s| = \Gamma(B_s^{even}) - \Gamma(B_s^{odd}))$

- $|\Gamma_{12}^s| = \Gamma(B \to f_{CP+}) - \Gamma(B \to f_{CP-}) \quad (|f\rangle = |f_{CP+}\rangle + |f_{CP-}\rangle)$
- In general $\Delta\Gamma_s = \Delta\Gamma_s^{CP} \cos\phi_s \quad (\Delta\Gamma_s^{CP}$: almost insensitive to NP as it is dominated by Cabibbo allowed tree level charged current transitions)
- $\Delta m_s$ very sensitive to NP
- NP will suppress $\Delta\Gamma_s$
- $\Delta\Gamma_s^{CP} > 0$ (calculated within SM). Model independently leads to:

* More CP even final states than CP odd in $B_s$ decays
* BR's into CP-specific states $(D_s^{(*)+} D_s^{(*)-})$ determine $\Delta\Gamma_s^{CP}$ NOT $\Delta\Gamma_s$

- To good accuracy and under assumptions which can be exptly. controlled

$$2\, BR[D_s^{(*)+} D_s^{(*)-}] \simeq \Delta\Gamma_s^{CP}[\frac{1+\cos\phi_s}{2\Gamma_L} + \frac{1-\cos\phi_s}{2\Gamma_H}] = \frac{\Delta\Gamma_s^{CP}}{\Gamma_s}[1 + \mathcal{O}(\frac{\Delta\Gamma_s}{\Gamma_s})]$$

$\Delta\Gamma_s^{CP}$ can be determined - sensitivity to NP$/\phi_s$ suppressed by $\frac{\Delta\Gamma_s^{CP}}{\Gamma_s}$

- Assumption that $b \to c\bar{c}s$ saturates $\Delta\Gamma_s$ is good to within a few $\%$

- $a_{fs} = Im\frac{\Gamma_{12}^s}{M_{12}^s} = |\frac{\Gamma_{12}^s}{M_{12}^s}| \sin\phi_s$: measures CP asymmetry in flavour specific decays ie $B \to f$ but not $\bar{B} \to f$. Examples: $B \to X\ell^+\nu_\ell$, $B_s \to D_s^-\pi^+$
- $a_{fs} = \frac{\Gamma(\bar{B}(t)\to f)-\Gamma(B(t)\to \bar{f})}{\Gamma(\bar{B}(t)\to f)+\Gamma(B(t)\to \bar{f})}$ Measures CP asymmetry in mixing
- Large $\Delta\Gamma_s$ implies - untagged data carries information on CPV
- Tagging not required $\Gamma[f,t] = \Gamma(\bar{B}(t) \to f) + \Gamma(B(t) \to f)$

$$a_{fs}^{untagged} = \frac{\Gamma[f,t]-\Gamma[\bar{f},t]}{\Gamma[f,t]+\Gamma[\bar{f},t]} = \frac{a_{fs}}{2}\left(1 - \frac{\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2)}\right)$$

- Time integrated asymmetry: $A_{fs}^{unt} = \frac{a_{fs}}{2}\frac{x^2+y^2}{x^2+1} \simeq \frac{a_{fs}}{2}$
- $x_s = \Delta m_s/\Gamma_s >> 1$ $y_s = \Delta\Gamma_s/(2\Gamma_s)$ $(|\Gamma_{12}^s| << |M_{12}^s|)$
- Only count say positive vs negative leptons from *untagged B decays*
- NP depletes $\Delta\Gamma_s$, but $|a_{fs}|$ can be greatly enhanced
- Using various relations $a_{fs} = \frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_s$

# What do we know and where do we stand?

| Quantity | SM expectation | Expt. |
|---|---|---|
| $\Delta m_s$ | $20.3 \pm 3.4$ ps$^{-1}$ | $17.31^{+0.33}_{-0.18} \pm 0.07$ ps$^{-1}$ |
| $\Delta\Gamma_s$ | $0.096 \pm 0.039$ ps$^{-1}$ | $0.13 \pm 0.09$ ps$^{-1}$ |
| $\frac{\Delta\Gamma_s}{\Gamma_s}$ | $0.127 \pm 0.024$ | $0.079 \pm 0.047$ |
| $\frac{\Delta\Gamma_s}{\Delta m_s} = \left\lvert\frac{\Gamma_{12}^s}{M_{12}^s}\right\rvert \cos\phi_s$ | $\mathcal{O}(\frac{m_b^2}{M_W^2}) \sim 0.005$ | $0.008$ (central) |
| $\lvert a_{fs}\rvert$ | $2 \times 10^{-5}$ | $0.025$ |
| $\phi_s$ | $\mathcal{O}(\lvert V_{us}\rvert^2 \frac{m_c^2}{m_b^2}) \sim 0.2^\circ$ | $-0.70^{+0.47}_{-0.39}$ |

- $\Delta m_s$ insensitive to phase of $M_{12}^s$
- Information on phase $\phi_s$ from $\mathcal{A}^{mix}_{B_s \to J/\psi\phi}$: requires tagging, $\Delta m_s$ resolution
- Untagged measurements: (a) $\Delta\Gamma_s$ (b) $a_{fs}$ (c) $B_s \to VV'$ ang. analysis

# Some Theory Details and Cautionary points

- $\Delta m \propto f_B^2 B_B$: two different definitions of $B_B$ are used in literature

(i) $\overline{MS}(\mu = m_b)$: $B_B \sim 0.85$ (ii) scheme invariant: $\hat{B}_B = 1.5 B_B \sim 1.3$

- What enters in $\Delta m$ calculation is not $m_t^{pole}$ but $\overline{MS}$ mass $\bar{m}_t < m_t^{pole}$

$$\Delta m \propto \lambda_t^2 {f_B}^2 \left\{ B_B(\mu_b) [\alpha_s(\mu_b)]^{-6/23} \left[ 1 + \frac{\alpha_s(\mu_b)}{4\pi} J_5 \right] \right\} \{ \eta_B(\bar{m}_t(\mu_t)) S_0(\bar{m}_t(\mu_t)) \}$$

- Important hadronic quantities $\langle B | \bar{q}_L \gamma_\mu b_L \bar{q}_L \gamma^\mu b_L | \bar{B} \rangle \propto f_B^2 B$

$$\langle B | \bar{b}_R q_L \bar{b}_R q_L | \bar{B} \rangle \propto f_B^2 B_S \qquad \langle B | \bar{b}_R^i q_L^j \bar{b}_R^j q_L^i | \bar{B} \rangle \propto f_B^2 \tilde{B}_S$$

- Till end of 2006, theory calculations of $\Delta\Gamma_s$ suffered from pathology: $1/m_b$ and $\alpha_s$ corrections were large, $B_S$ piece dominated implying $\Delta\Gamma/\Delta m \propto B_S/B$

- Lenz, Nierste '06: Change of basis - $B$ term dominates, better control over $1/m_b$ corrections (from $33\% \to 19\%$), reduced scale uncertainty

- Info. on $\phi_s$ desirable - Can provide first glimpse of NP

# Semileptonic Asymmetries

- Same sign dimuon asymmetry $A_{SL} = 4\,\frac{N_{b\bar{b}\to\ell^+\ell^+X} - N_{b\bar{b}\to\ell^-\ell^-X}}{N_{b\bar{b}\to\ell^+\ell^+X} + N_{b\bar{b}\to\ell^-\ell^-X}}$
- B-factories, flavour specific CP asym. $(B_d)$: $A_{SL}^{\Upsilon(4S)} = A_{SL}^d = 4\,\frac{\mathrm{Re}\,\varepsilon_{B_d}}{1+|\varepsilon_{B_d}|^2}$
- Hadron colliders, $B_d$ and $B_s$ contribute: $A_{SL}^{\mathrm{TeV}} \simeq 0.6 A_{SL}^d + 0.4 A_{SL}^s$ [Nir etal]
- D∅ uses a slightly different expression - results depend on form used
- $A_{SL}^s = \frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_s$: depends on $A_{SL}^d$ [Recall: $|A_{SL}^s| < \frac{\Delta\Gamma_s^{\mathrm{SM}}}{\Delta m_s} \leq 0.005$]
- D∅ Measurement: $A_{SL}^{\mathrm{TeV}} = -0.0092 \pm 0.0044 \pm 0.0032(\mathrm{D\emptyset})$
- $A_{SL}^d = +0.0011 \pm 0.0055$ [Nir etal av.] $\Rightarrow A_{SL}^s = -0.025 \pm 0.016$
- $A_{SL}^d|_{SM} = -(0.00048)^{+0.00010}_{-0.00012} \Rightarrow A_{SL}^s = -0.024 \pm 0.014$
- D∅ analysis, $A_{SL}^d = -0.0047 \pm 0.0046 \Rightarrow A_{SL}^s = -0.0064 \pm 0.0101$
- In any case, $A_{SL}^s$ central value different from expectations: errors are large!!

• Time int. untagged single muon asymmetry:

$$A_{SL}^{s,\,\mathrm{untag}} = \frac{N_{B_s \to \mu^+ D_s^- X} - N_{B_s \to \mu^- D_s^+ X}}{N_{B_s \to \mu^+ D_s^- X} + N_{B_s \to \mu^- D_s^+ X}} \cong \frac{1}{2} A_{SL}^s = +0.0123 \pm 0.0097 \pm 0.0017 (\mathrm{D}\emptyset)$$

• $A_{SL}^s$ from dimuon and single muon asym. - similar mag., opposite signs

• Due to large errors, consistent with zero. But large central values

• Dimuon measurement has statistical advantage but seems already systematically limited

• Need to disentangle $A_{SL}^s$ from $A_{SL}^d$ in case of dimuon asym.

• The systematic error in single muon measurement is smaller than the rough bound - so with better statistics, it may stand better chance

• At LHCb, single muon channel may be interesting modulo the issue of production bias - $pp$ vs $p\bar{p}$

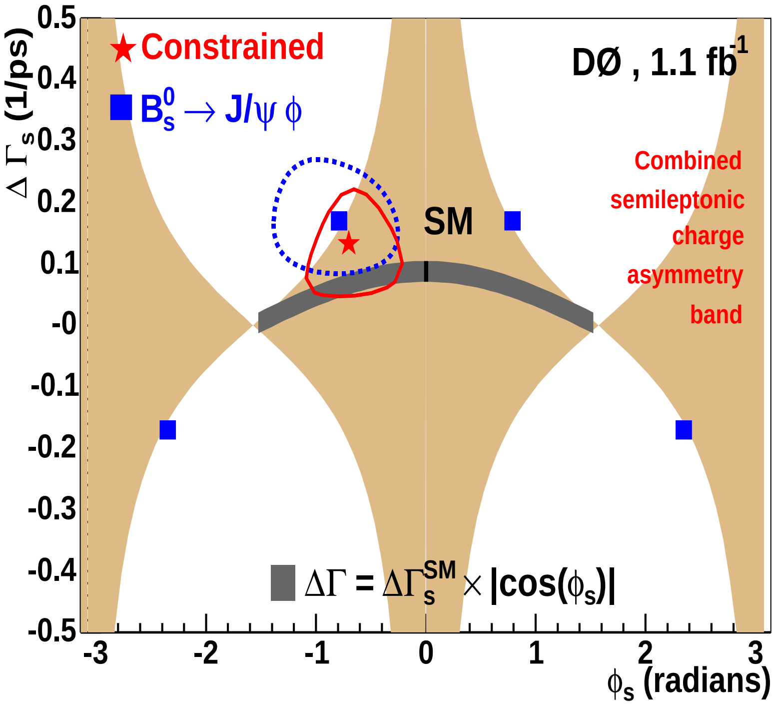
# $\Delta\Gamma_s$ measurements

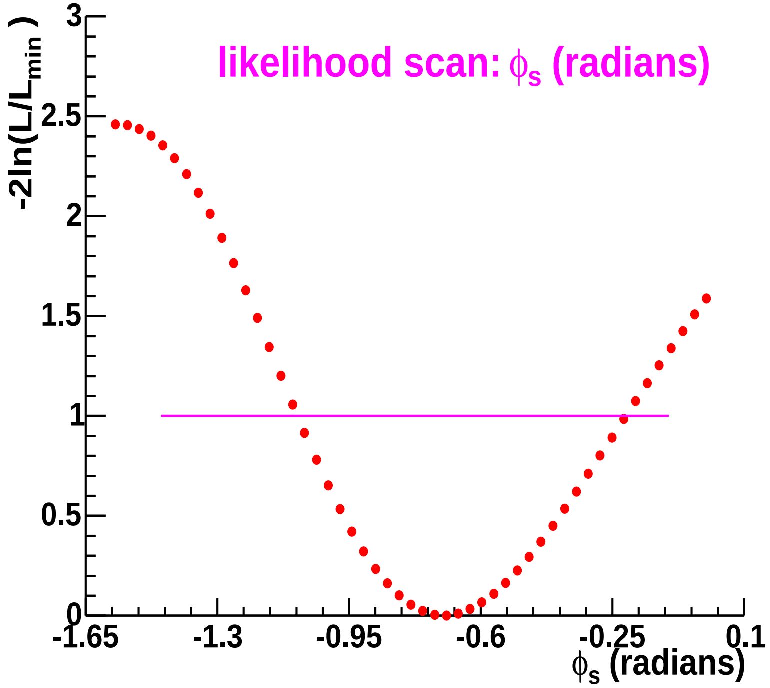
- $B_s \to J/\psi\phi$ is the Golden mode for width difference
- Different CP components mix and interfere: $\sin\phi_s$ term in the rate
- Performing angular analysis of untagged $B_s \to J/\psi\phi$, DØ obtains (free $\phi_s$):

$\phi_s = -0.79 \pm 0.59,\ \Delta\Gamma_s = 0.17 \pm 0.09\ \mathrm{ps}^{-1}$ [$|\cos\phi_s| = 0.22$ to $0.98$]

- Keeping $\phi_s$ fixed at ZERO, DØ obtains: $\Delta\Gamma_s = 0.12^{+0.08}_{-0.10}$ ps$^{-1}$
- Cosistent with scaling $\Delta\Gamma_s = 0.17$ ps$^{-1}$ by $\cos\phi_s$ [$\phi_s \sim 1\sigma$ from zero]
- Is it possible to have a large phase and saturate $A^s_{SL}$ bound? Yes
- Take a sequential four generation model as an example: $\phi_s^{SM4} \sim -0.6$
- Any other model which satisfies the constraints is an equally good example

# DØ Combined analysis




- Comined analysis of $\Delta\Gamma_s$ from $B_s \to J/\psi\phi$, semileptonic asymmetries and flavour specific $B_s$ lifetime DØ obtains: for the preferred solution with $\phi_s < 0$, and a particular choice of strong phases

$$\Delta\Gamma_s = 0.13 \pm 0.09 \text{ ps}^{-1} \qquad \phi_s = -0.70^{+0.47}_{-0.39}$$

# $\Delta\Gamma_s/\Gamma_s$ measurement

- Recall that $2\, BR[D_s^{(*)+} D_s^{(*)-}] \simeq \frac{\Delta\Gamma_s^{CP}}{\Gamma_s}[1 + \mathcal{O}(\frac{\Delta\Gamma_s}{\Gamma_s})]$
- DØ has measured this mode and obtains, $\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} = 0.079 \pm 0.047$
- Good agreement with SM (small CPV) $\frac{\Delta\Gamma_s}{\Gamma_s}|_{SM} = 0.127 \pm 0.024$
- DØ results are better than the CDF'04 results obtained from $B_s \to J/\psi\phi$

  $\frac{\Delta\Gamma_s}{\Gamma_s} = 0.65^{+0.25}_{-0.33} \pm 0.01$ $\Delta\Gamma_s = (0.47^{+0.19}_{-0.24} \pm 0.01)$ ps$^{-1}$
- Comparing the DØ results with SM expectations on $\Delta\Gamma_s/\Gamma_s$, there seems no sign of any large deviation
- No large CPV phase seems to be required - to be contrasted with the combined analysis where a large central value is obtained from the fit

# Road ahead...

- $M_{12}^s = R_s e^{i\phi_s} (M_{12}^s)^{SM}$: $\Delta m_s = R_s (M_{12}^s)^{SM}$ $\Delta\Gamma_s = \Delta\Gamma_s^{SM} \cos\phi_s$

Correlation: $A_{SL}^s = -Re\left(\frac{\Gamma_{12}^s}{M_{12}^s}\right)^{SM} \frac{\sin\phi_s}{R_s}$ $S_{\psi\phi(CP=+)} = -\sin\phi_s$

- Dimuon asymmetry harder at hadron colliders due to loss of coherence between $B$ and $\bar{B}$: single muon channel possible
- Good case for Super-B at $\Upsilon(5S)$: no oscillation measurement required
- Complimentary to mixing $\mathcal{A}_{B_s \to J/\psi\phi}^{mix}$: yet some correlation
- Can provide the much desired information on the phase in $B_s$ mixing
- Untagged, non-oscillation measurement can yield the first hints of NP, if present
- With more data on the way, maybe Tevatron will show some clear direction before LHCb