NEW PHYSICS IN B_s-MIXING

AND DECAYS

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Implications of LHCb measurements
and future prospects

– B_s Mixing –

Introduction

New physics in M_{12}

. . . and Γ_{12}

B_q^0-meson mixing: ΔM_q & $\Delta\Gamma_q$

Flavour eigenstates $\overline{B}_q = (b\bar{q})$ and $B_q = (\bar{b}q)$ with $q = d, s$ (PDG-convention)

TIME EVOLUTION

$$i\frac{d}{dt}\begin{pmatrix}|B^q(t)\rangle \\ |\overline{B}^q(t)\rangle\end{pmatrix} = \left[M^q - i\,\frac{\Gamma^q}{2}\right]\begin{pmatrix}|B^q(t)\rangle \\ |\overline{B}^q(t)\rangle\end{pmatrix}$$

2×2-matrices: $\quad M^q = (M^q)^\dagger, \quad \Gamma^q = (\Gamma^q)^\dagger$

CPT-invariance

$$M_{11}^q = M_{22}^q, \quad M_{12}^q = (M_{21}^q)^*, \quad \Gamma_{11}^q = \Gamma_{22}^q$$

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Heavy & light mass eigenstates B_H^q and B_L^q from diagonalisation of $(M - i\,\Gamma/2)$

$\Rightarrow$ eigenvalues $M_{H,L}^q$ and $\Gamma_{L,H}^q$ (all positive)

$$M_{11} = M_{22} = \frac{M_H^q + M_L^q}{2}$$

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$\Rightarrow$ ΔM_q determines oscillation frequency

$\Rightarrow$ $\Delta\Gamma_q$ corresponds to "damping"

2 OBSERVABLES

$$\Delta M_q = M_H^q - M_L^q = 2\,|M_{12}^q| + \ldots \geqslant 0$$

$$\Delta\Gamma_q = \Gamma_L - \Gamma_H = 2\,|\Gamma_{12}^q|\cos(\phi_q) + \ldots \gtrless 0$$

$\Longrightarrow$ 3 parameters:

$$|M_{12}^q|, \quad |\Gamma_{12}^q|, \quad \phi_q = \arg\left(-\frac{M_{12}^q}{\Gamma_{12}^q}\right)$$

ΔM_s from

- CDF (2006 1/fb, hadr. + semi-lept. B_s decays) [CDF hep-ex/0609040]
- LHCb (2011 36/pb, $B_s \to D_s^- \pi^+$) [LHCb arXiv:1112.4311]

$$\Delta M_s|_{\rm exp} = (17.731 \pm 0.045)/ps \qquad \Leftrightarrow \qquad \Delta M_s|_{\rm SM} = (17.3 \pm 2.6)/ps$$

experimental precision ahead of theory → lattice results needed [Lenz/Nierste arXiv:1102.4274]

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Γ_s, $\Delta\Gamma_s$ and ϕ_f : Combined fit from $\overline{B_s}$, $B_s \to f$ (time-dependent + tagged)

$\Rightarrow f = J/\psi + \phi,\ J/\psi + \pi\pi,\ \ldots$

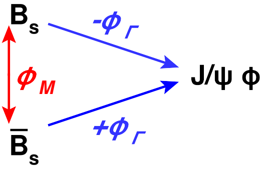
In literature several conventions of ϕ_f, for example $f = J/\psi + \phi$

- LHCb [arXiv:1112.3183]:

$$\phi_s|_{\text{SM}} = \phi_M - 2\phi_\Gamma \approx -2\arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right] = -2\,\beta_s$$

- Lenz/Nierste/CKMfitter [arXiv:1203.0238]:

$$2\,\phi_s^{\psi\phi}|_{\text{SM}} = 2\,\beta_s = (2.1 \pm 0.1)^\circ$$



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$-2\,\phi_s^{\psi\phi} = (-44^{+17}_{-21})^\circ$	CDF 1.35/fb and DØ 2.8/fb [HFAG 2011]
$= (-43.5^{+21.8}_{-20.6} \pm 1.2)^\circ$	DØ 6.1/fb [Conference Note 6098]
$\in [-59.6, -2.3]^\circ$	CDF 5.2/fb [arXiv:1112.1726]
$= (8.6 \pm 10.3 \pm 3.4)^\circ$	LHCb 0.37/fb ($\to J/\psi\,\phi$) [arXiv:1112.3183]
$= (-25.2 \pm 25.2 \pm 1.2)^\circ$	LHCb 0.41/fb ($\to J/\psi\, f_0$) [arXiv:1112.3056]
$= (-0.06 \pm 5.79 \pm 1.55)^\circ$	LHCb 1/fb ($\to J/\psi\,\phi$) [LHCb-CONF-2012-002]
$= (-1.1 \pm 9.7 \pm 1.1)^\circ$	LHCb 1/fb ($\to J/\psi\, f_0$) [LHCb-CONF-2012-006]
$= (-0.11 \pm 4.76 \pm 1.55)^\circ$	LHCb 1/fb combined $\to J/\psi\,\phi$ and $\to J/\psi\, f_0$

$$-2\,\phi_s^{\psi\phi}|_{\rm SM} = (-2.1 \pm 0.1)^\circ$$

CP-asymmetries: $a_{\mathrm{fs}}^{d,s}$ & A_{SL}^{b}

a_{fs}^{q} = CP-asym's in flavour specific $B_q \to f$

$$a_{fs}^{q} = \frac{\Gamma\left[\overline{B_q}(t) \to f\right] - \Gamma\left[B_q(t) \to \bar{f}\right]}{\Gamma\left[\overline{B_q}(t) \to f\right] + \Gamma\left[B_q(t) \to \bar{f}\right]} = \frac{|\Gamma_{12}^{q}|}{|M_{12}^{q}|} \sin(\phi_q)$$

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Like-sign dimuon charge asymmetry
of semi-leptonic b-hadron decays

$$A_{\rm SL}^b = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

$N_b^{++(--)}$ = # of evts with 2 μ^+ (μ^-)

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$$\boxed{A_{\rm SL}^b = C_d\, a_{fs}^d + C_s\, a_{fs}^s}$$

C_q depend on production rate of B_q

$A_{\rm SL}^b$ relates B_d- and B_s-mixing !!!

$C_d \approx 0.55$, $C_s \approx 0.45$

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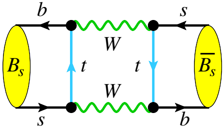
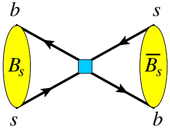
A_{SL}^{b}: DØ (9/fb) measurement deviates by 3.9 σ from SM

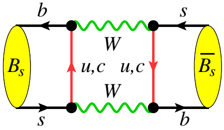
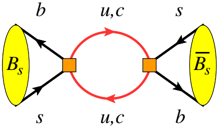
a_{fs}^{q}: measurements with large errors

SM = [Lenz/Nierste arXiv:1102.4274]

$[\times 10^{-3}]$	SM	measurement	
A_{SL}^{b}	-0.24 ± 0.04	$-7.87 \pm 1.72 \pm 0.93$	[DØ arXiv:1106.6308]
a_{fs}^{d}	-0.41 ± 0.06	-4.7 ± 4.6	[HFAG arXiv:1010.1589] (*B*-factories)
		-0.5 ± 5.6	[HFAG 2011] (*B*-factories)
a_{fs}^{s}	-0.019 ± 0.003	-1.7 ± 9.2	[DØ arXiv:0904.3907]

In the SM . . .

$M_{12} =$ [] $\Rightarrow$ $C_i \times$ []

$\Gamma_{12} = \mathrm{Im}$[] $\Rightarrow$ $C_a C_b^* \times \mathrm{Im}$[]

In the SM . . .

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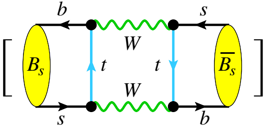
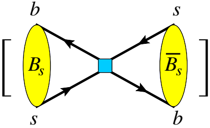
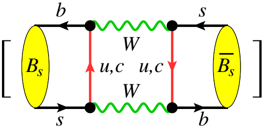


$\Rightarrow$ $C_i \times$

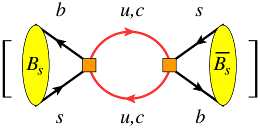


$\Delta B = 2 \sim M_W^2/\Lambda_{\rm NP}^2$

$\Gamma_{12} = \mathrm{Im}$



$\Rightarrow$ $C_a C_b^* \times \mathrm{Im}$



$(\Delta B = 1)^2 \sim M_W^4/\Lambda_{\rm NP}^4$

For heavy new physics ($M_W \lesssim \Lambda_{\rm NP}$) $\rightarrow$ can be described by dim-6 op's

- $\Delta B = 2 \rightarrow [\bar{s}\Gamma b][\bar{s}\Gamma' b]$
- $\Delta B = 1 \rightarrow [\bar{s}\Gamma b][\bar{f}_1 \Gamma' f_2]$ with "$(m_{f_1} + m_{f_2}) \lesssim M_{B_s}$" $\Rightarrow f = (u, d, s, c)$ and (e, μ, τ) (or BSM f =???)

New physics in M_{12}^s: 2010 vs 02/2012 [Lenz/Nierste/CKMfitter arXiv:1008.1593, arXiv:1203.0238]

- perform global CKM-fit
- use parametrisation of New Physics (NP) in:

$$M_{12}^q = M_{12}^{\mathrm{SM},q} \cdot \Delta_q, \qquad \Delta_q = |\Delta_q| e^{i\phi_q^\Delta}, \qquad q = d, s$$

- 2 complex NP parameters → 4 dimensional NP parameter space
- B_d- and B_s-sector connected via A_{SL}^b

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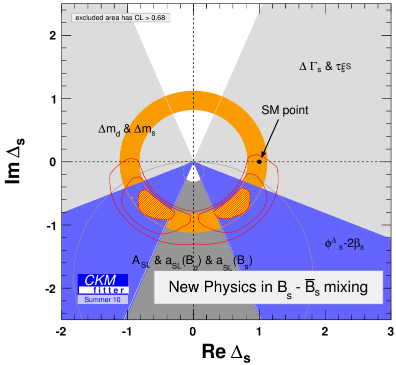
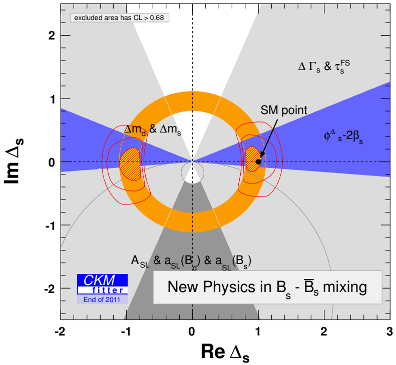
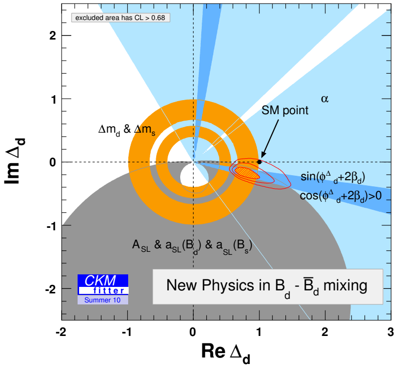


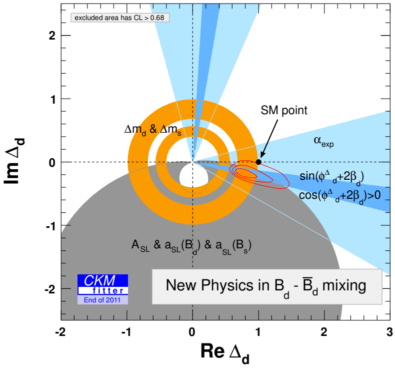


	2010	02/2012 (before Moriond)
p-value for hypothesis $\Delta_s = 1$ (2D)	$2.7\,\sigma$	$0.8\,\sigma$

$\Rightarrow$ tension with SM in B_s-system gone due to new $\phi_s^{\psi\phi}$ measurements of LHCb

New physics in M_{12}^d: 2010 vs 02/2012 [Lenz/Nierste/CKMfitter arXiv:1008.1593, arXiv:1203.0238]





2010	02/2012 (before Moriond)
p-value for hypothesis $\Delta_d = 1$ (2D)	
$2.7\,\sigma$	$3.2\,\sigma$
for SM hypothesis $\Delta_d = \Delta_s = 1$ (4D)	
$3.6\,\sigma$	$2.7\,\sigma$

$\Rightarrow$ tension in B_d-system augmented, but overall tension with SM decreased

New physics in Γ_{12}^q:

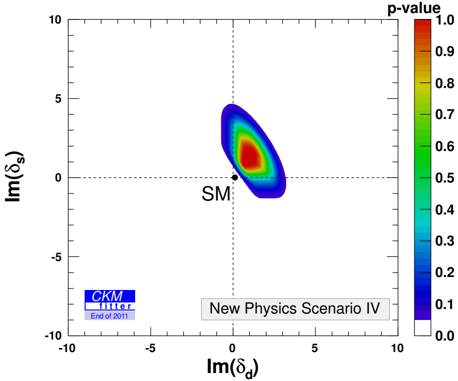
[Lenz/Nierste/CKMfitter arXiv:1008.1593, arXiv:1203.0238]

Model-ind. parametrisation of NP in Γ_{12}^q

$$\delta_q = \frac{\Gamma_{12}^q / M_{12}^q}{\text{Re}\left(\Gamma_{12}^{\text{SM},q} / M_{12}^{\text{SM},q}\right)}$$

$$\delta_d^{\text{SM}} = 1 + 0.097\, i$$
$$\delta_s^{\text{SM}} = 1 - 0.0059\, i$$

but does NOT account for NP in $\Delta B = 1$ decays



- p-value of SM hypothesis $(\Delta_d = \Delta_s = 1,\, \delta_q = \delta_q^{\text{SM}})$:

  $2.7\,\sigma$

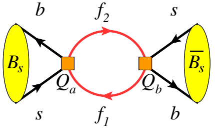
- no NP in B_s $(\Delta_s = 1,\, \delta_s = \delta_s^{\text{SM}})$ gives large contributions in Γ_{12}^d:

  $$\text{Im}\,\delta_d = 1.48^{+0.92}_{-0.65}$$

New physics in Γ_{12}^s . . .

. . . using $\Delta B = 1$ operators $\mathcal{O}_i = [\bar{s}\Gamma b][\bar{f}_1 \Gamma' f_2]$ with light $f_{1,2}$

$$\Gamma_{12} = \Gamma_{12}^{\rm SM} + C_a C_b^* \times \mathrm{Im}\Big[\quad\Big]$$



$\Rightarrow$ subject to constraints since contribute to: Γ_s, $\tau(B_s)/\tau(B_d)$, $b \to s \bar{f}_1 f_2$ decays ...

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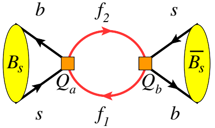
$$\Gamma_{12} = \Gamma_{12}^{\rm SM} + C_a C_b^* \times \mathrm{Im}\Big[$$  $$\Big]$$

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. . . from $b \to s\tau^+\tau^-$:

[Dighe/Kundu/Nandi arXiv:0705.4547, Bauer/Dunn 1006.1629, CB/Haisch 1109.1826]

Could be a candidate → only weak direct constraints:

- $Br(B^+ \to K^+\tau^+\tau^-) < 3.3 \cdot 10^{-3}$ @ 90% CL [Babar @ ICHEP 2010]
- $Br(B_s \to \tau^+\tau^-) \lesssim 3\%$ @ 90% CL only indirectly from $\tau(B_s)/\tau(B_d)$

  → assuming no NP in $\tau(B_d)$

  → based on LHCb measurement: $\tau(B_s)/\tau(B_d) - 1 = (0.4 \pm 1.9)\%$ [LHCb-CONF-2011-049]

  SM prediction: $\in [-0.4, 0.0]\%$ [Lenz/Nierste 1102.4274]

- $Br(B \to X_s\tau^+\tau^-) \lesssim 5\%$ LEP: B decays with large $\not{E}$ [Grossman/Ligeti/Nardi hep-ph/9607473]

  $Br(B \to X_s\tau^+\tau^-) \lesssim 2.5\%$ → bckg to $Br(B \to K\ell\bar{\nu}_\ell + \text{anything}) = (4\ldots6 \pm 0.5) \cdot 10^{-2}$

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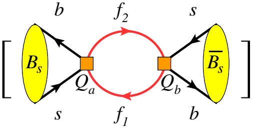

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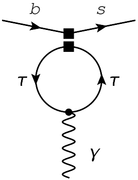
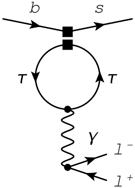
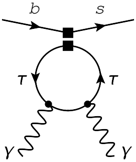
. . . from $b \to s\tau^+\tau^-$:

[CB/Haisch arXiv:1109.1826]

Also indirect constraints due to operator mixing







$\mathcal{O}_{TR} \to \mathcal{O}_7$ $\mathcal{O}_{VLA} \to \mathcal{O}_9$ $\mathcal{O}_{SAB} \to \vec{\varepsilon}_1 \cdot \vec{\varepsilon}_2$

$\mathcal{O}_{TL} \to \mathcal{O}_{7'}$ $\mathcal{O}_{VRA} \to \mathcal{O}_{9'}$ $\mathcal{O}_{SAB}, \mathcal{O}_{VAB} \to \vec{\varepsilon}_1 \times \vec{\varepsilon}_2$

Used measurements

$B \to X_s\gamma$:	Br
$B \to K^*\gamma$:	Br, S, A_I
$B_s \to \gamma\gamma$:	Br
$B \to X_s \bar{\ell}\ell$:	$\langle BR \rangle$ (low-q^2)
$B \to K \bar{\ell}\ell$:	$\langle BR \rangle$
$B \to K^* \bar{\ell}\ell$:	$\langle BR \rangle$, $\langle A_{\rm FB} \rangle$, $\langle F_L \rangle$

SAB op's neither mix into $b \to s\gamma$ nor $b \to s\bar{\ell}\ell$, but contribute to ME of $b \to s\gamma\gamma$

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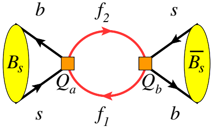
. . . using $\Delta B = 1$ operators $\mathcal{O}_i = [\bar{s}\Gamma b][\bar{f}_1 \Gamma' f_2]$ with light $f_{1,2}$

$$\Gamma_{12} = \Gamma_{12}^{\rm SM} + C_a C_b^* \times \text{Im}\Big[\quad\Big]$$



$\Rightarrow$ subject to constraints since contribute to: Γ_s, $\tau(B_s)/\tau(B_d)$, $b \to s \bar{f}_1 f_2$ decays ...

. . . from $b \to s \tau^+\tau^-$:

[CB/Haisch arXiv:1109.1826 update]

Upper bounds assuming single operator dominance and complex C_i:

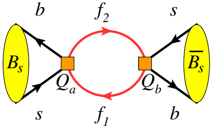
$\lvert C_i(m_b)\rvert$	$B_s \to \bar{\tau}\tau$	$B \to X_s \bar{\tau}\tau$	$B^+ \to K^+ \bar{\tau}\tau$	bound	ind. process
SAL SAR	< 0.5	< 2.9	< 0.8	< 3.4 < 2.3	$B_s \to \gamma\gamma$ —"—
VAL VAR	< 1.0	< 1.5	< 0.8	< 1.1 < 1.0	$b \to s + (\gamma, \bar{\ell}\ell)$ —"—
TL TR	–	< 0.4	< 0.4	< 0.06 < 0.09	—"— —"—

$\mathcal{O}_{XAB} = [\bar{s}\, X\, P_A\, b][\bar{\tau}\, X\, P_B\, \tau]$ with $X = (S = 1, V = \gamma^\mu, T = \sigma^{\mu\nu})$

$A, B = L, R$ and $P_{L,R} = (1 \mp \gamma_5)/2$

New physics in Γ_{12}^s . . .

. . . using $\Delta B = 1$ operators $\mathcal{O}_i = [\bar{s}\Gamma b][\bar{f}_1\Gamma' f_2]$ with light $f_{1,2}$

$$\Gamma_{12} = \Gamma_{12}^{\rm SM} + C_a C_b^* \times \text{Im}\Big[$$  $$\Big]$$

⇒ subject to constraints since contribute to: Γ_s, $\tau(B_s)/\tau(B_d)$, $b \to s \bar{f}_1 f_2$ decays ...

. . . from $b \to s\tau^+\tau^-$:

NP contribution to $\Gamma_{12}^s = (\Gamma_{12}^s)_{\rm SM} R_\Gamma e^{i\phi_\Gamma}$

Assuming single operator dominance

$$(R_\Gamma)_{SAB} < 1 + (0.4 \pm 0.1)\,|C_{SAB}(m_b)|^2 \lesssim 1.15$$

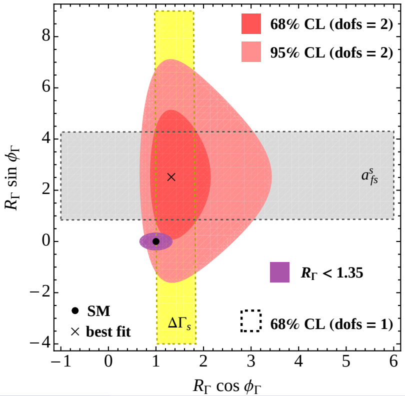
$$(R_\Gamma)_{VAB} < 1 + (0.4 \pm 0.1)\,|C_{VAB}(m_b)|^2 \lesssim 1.35$$

$$(R_\Gamma)_{TA} < 1 + (0.9 \pm 0.2)\,|C_{TA}(m_b)|^2 \lesssim 1.008$$

⇒ at most 35% deviation from SM: $R_\Gamma = 1$

(in fit a_{fs}^s calculated from experimental A_{SL}^b and a_{fs}^d)

[CB/Haisch arXiv:1109.1826 update]



- Assuming New Physics in B_q-mixing improves the fit compared to SM
- Including LHCb results (before Moriond) ($\Delta\Gamma_s$, $\phi_s^{\psi\phi}$) helps SM 'performance" in B_s-sector
- DØ measurement of A_{SL}^b connects B_d- and B_s-sectors
  $\rightarrow$ SM more "in trouble" in B_d-sector
- New physics in Γ_{12}^q can help, however in $q = s$ many strong constraints
  $\rightarrow$ Γ_{12}^d not so strongly constraint
- Despite the loose constraints on $b \rightarrow s\,\tau^+\tau^-$,
  allow only about $\mathcal{O}(30\,\%)$ deviation of Γ_{12}^s from SM

SUMMARY 2/2

- Pursue a measurement of a^d_{fs}, a^s_{fs} or linear combination $(a^s_{fs} - a^d_{fs})$
- Improve measurement of life-times
- Independent bound on $B_s \to \tau^+\tau^-$ could be useful
- In view of future high precision in $\phi_s^{\psi\phi}$,

  $\to$ penguin pollution in $B_s \to J/\psi\phi$ or $B_s \to J/\psi(\pi\pi)$

  use control channels
  $B_s \to J/\psi K^{*0}$ [Faller/Fleischer/Mannel arXiv:0810.4248]
  $B_d \to J/\psi f_0$ [Fleischer/Knegjens/Ricciardi arXiv:1109.1112]
- Measure penguin-dominated $B_{s,d}(\to \phi\phi, K^{*0}\bar{K}^{*0}, \phi K^0_S, \ldots)$ decays to learn about possible NP-phases

  $\to$ penguin pollution in $B_s \to J/\psi\phi$ or $B_s \to J/\psi(\pi\pi)$