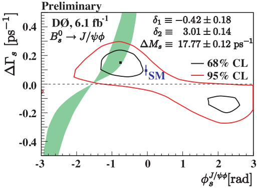
Probing New Physics with B_s mass-eigenstate asymmetries

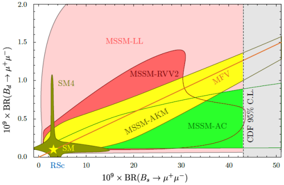
Rob Knegjens

IAS TUM Institute for Advanced Study

No smoking gun signal of New Physics from LHC

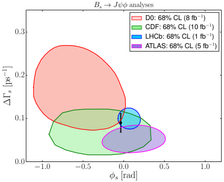
$B_s \to J/\psi\phi$ — 2010 — $B_s \to \mu^+\mu^-$

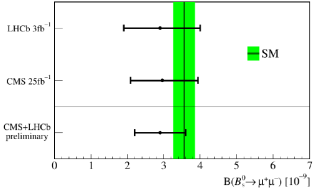




Straub; 1012.3893

⇓ — 2014 — ⇓





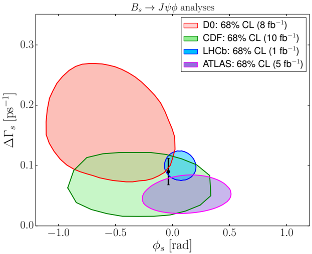
Smallish New Physics in B_s mixing?

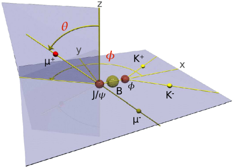
LHCb $B_s \to J/\psi\phi$ analysis (1 fb^{-1}):

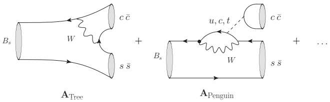
$$\phi_s = (4.0 \pm 5.2)^\circ$$

$$\Gamma_\mathrm{L} - \Gamma_\mathrm{H} = 0.100 \pm 0.017\ \mathrm{ps}^{-1}$$

Compared to $\phi_s^{\mathrm{SM}} = -(2.11 \pm 0.08)^\circ$







- Complicated experimental analysis
- Phase shift from penguin topologies?

Measure: $\phi_s + \Delta\phi^\lambda_{J/\psi\phi}$ for angular components λ

$$\Delta\phi^\lambda_{J/\psi\phi} = \mathcal{O}(1^\circ)$$

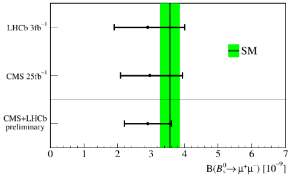
(See Faller, Fleischer, Mannel; 0810.4248)

Complementary analyses desirable

Smallish New Physics in $B_s \to \mu^+\mu^-$?

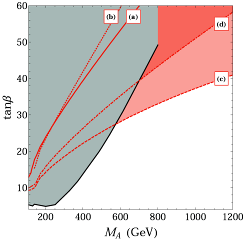
LHCb + CMS combined:

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$



Particularly sensitive to **scalar operators:**

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) \propto m_\mu^2 \left[\left| (C_{10}^{\mathrm{SM}} + C_{10}^{\mathrm{NP}} - C'_{10}) + \frac{m_{B_s}}{2m_\mu}(\boldsymbol{C_P} - \boldsymbol{C'_P}) \right|^2 + \left| \frac{m_{B_s}}{2m_\mu}(\boldsymbol{C_S} - \boldsymbol{C'_S}) \right|^2 \right]$$



Altmannshofer et al.; 1211.1976,

For example: MSSM with large $\tan\beta$:

$$\boldsymbol{C_S} \simeq -\boldsymbol{C_P} \approx \frac{m_\mu m_b}{8\pi\,\alpha} \frac{\tan^3\beta}{M_A^2} \frac{\mu A_t}{M_{\tilde{t}_L}^2}$$

- Constructive interference with SM quite constraining
- Destructive interference with SM less so

Complementary observables desirable

Complementary strategies to hunt for New Physics

- **Extracting CKM angle γ:**
  $B_s \to D_s^{\pm(*)} K^{\mp}$
  $B_s \to K^+ K^-$
  with R.Fleischer, Nikhef LHCb group

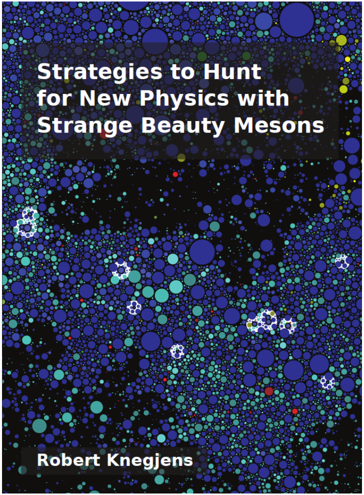
- **Probing NP in B_s^0–$\overline{B}_s^0$ mixing:**
  $B_s \to K^+ K^-$
  $B_s \to J/\psi f_0(980)$
  $B_s \to J/\psi \eta^{(\prime)}$
  with R.Fleischer, G.Ricciardi

- **Identifying NP in $B_s \to \mu^+\mu^-$**
  with R.Fleischer, A.Buras, J.Girrbach, F.De Fazio, M.Nagai

Recurring observable:

$$\mathcal{A}_{\Delta\Gamma}^{f} = \frac{\Gamma(B_{s,\mathrm{H}} \to f) - \Gamma(B_{s,\mathrm{L}} \to f)}{\Gamma(B_{s,\mathrm{H}} \to f) + \Gamma(B_{s,\mathrm{L}} \to f)}$$

"mass-eigenstate rate asymmetries"

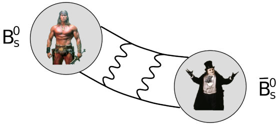


cover image: http://paperscape.org

B_s mass-eigenstates

Flavour basis $\boldsymbol{B_s^0}$, $\boldsymbol{\bar{B}_s^0}$:

$$i\frac{d}{dt}\begin{pmatrix} |B_s^0(t)\rangle \\ |\overline{B}_s^0(t)\rangle \end{pmatrix} = \begin{pmatrix} M_0 - \frac{i}{2}\Gamma_0 & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M_0 - \frac{i}{2}\Gamma_0 \end{pmatrix}\begin{pmatrix} |B_s^0(t)\rangle \\ |\overline{B}_s^0(t)\rangle \end{pmatrix}$$



"Normal" Modes →

Mass basis:

$$\left|\boldsymbol{B}_{s,{}^{\mathrm{H}}_{\mathrm{L}}}\right\rangle = p|\boldsymbol{B_s^0}\rangle \pm q|\boldsymbol{\bar{B}_s^0}\rangle$$

Well defined **masses** and **lifetimes**

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} = -e^{-i\,\phi_s}\left[1 - \frac{1}{2}\underbrace{\mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)}_{=\,a_{\mathrm{SL}}^s\,\approx\,0} + \mathcal{O}\left(\left|\frac{\Gamma_{12}}{M_{12}}\right|^2\right)\right]$$

$$\phi_s \equiv \arg(M_{12}) \overset{\mathrm{SM}}{=} 2\,\beta_s = -(2.1 \pm 0.1)^\circ$$

B_s decay width difference

$$K_\mathrm{S} \approx K_+ \to \pi\pi$$

$$y_K = \frac{\Gamma_\mathrm{L} - \Gamma_\mathrm{S}}{\Gamma_\mathrm{L} + \Gamma_\mathrm{S}} \approx -1$$

$$\overset{\text{analogously}}{\Longrightarrow}$$

$$\mathcal{CP}|\boldsymbol{B_{s,\pm}}\rangle = \pm|\boldsymbol{B_{s,\pm}}\rangle$$

$$\boldsymbol{B_{s,+}} \to D_s^{(*)}\bar{D}_s^{(*)}, \ldots$$

$$\boxed{\boldsymbol{y_s} \equiv \frac{\Gamma_\mathrm{L} - \Gamma_\mathrm{H}}{\Gamma_\mathrm{L} + \Gamma_\mathrm{H}} = ?}$$

In Standard Model expect $\phi_s \approx -2.1°$:

$$\begin{pmatrix} |\boldsymbol{B_{s,\mathrm{L}}}\rangle \\ |\boldsymbol{B_{s,\mathrm{H}}}\rangle \end{pmatrix} = e^{-i\phi_s/2} \begin{pmatrix} \cos(\phi_s/2) & i\sin(\phi_s/2) \\ i\sin(\phi_s/2) & \cos(\phi_s/2) \end{pmatrix} \begin{pmatrix} |\boldsymbol{B_{s,+}}\rangle \\ |\boldsymbol{B_{s,-}}\rangle \end{pmatrix}$$

(convention dependent)

Estimate using Heavy Quark Expansion:

$$\boldsymbol{y_s}|_\mathrm{SM} = 0.067 \pm 0.016$$

A. Lenz, U. Nierste; 1102.4274

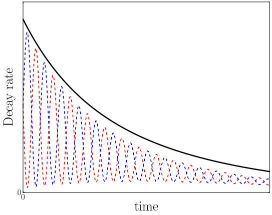
Indeed non-vanishing: *LHCb collaboration; 1304.2600*

$$\text{LHCb } B_s \to J/\psi\,\phi \text{ analysis}: \quad \boxed{\boldsymbol{y_s}|_\mathrm{LHCb} = 0.075 \pm 0.012}$$

The untagged decay rate

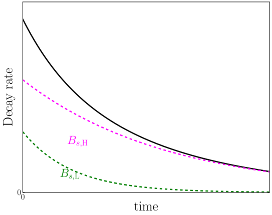
$$\langle \Gamma(B_s(t) \to f) \rangle = \frac{1}{N_{B_s}} \frac{dN_e(B_s \to f)}{dt} = \ldots$$

Flavour basis



$$\Gamma(B_s^0(t) \to f) + \Gamma(\bar{B}_s^0(t) \to f)$$

Mass e-state basis



$$\Gamma(B_{s,\mathrm{H}} \to f)\, e^{-\Gamma_{\mathrm{H}} t} + \Gamma(B_{s,\mathrm{L}} \to f)\, e^{-\Gamma_{\mathrm{L}} t}$$

$$\langle \Gamma_f \rangle = \left(\Gamma(B_{s,\mathrm{H}} \to f) + \Gamma(B_{s,\mathrm{L}} \to f)\right) e^{-t/\tau_{B_s}} \left\{ \cosh\left(y_s\, t/\tau_{B_s}\right) + \mathcal{A}^f_{\Delta\Gamma} \sinh\left(y_s\, t/\tau_{B_s}\right) \right\}$$

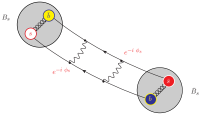
$$\boxed{\mathcal{A}^f_{\Delta\Gamma} = \frac{\Gamma(B_{s,\mathrm{H}} \to f) - \Gamma(B_{s,\mathrm{L}} \to f)}{\Gamma(B_{s,\mathrm{H}} \to f) + \Gamma(B_{s,\mathrm{L}} \to f)}}$$

$\mathcal{A}^f_{\Delta\Gamma}$: mass eigenstate rate asymmetry

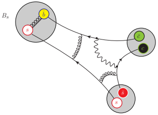
Consider: $B_s \to f$ with $\mathcal{CP}|f\rangle = \eta_f |f\rangle$

$$\lambda_f \equiv \frac{q}{p}\,\frac{A(\overline{B}^0_s \to f)}{A(B^0_s \to f)} = -\eta_f\, e^{-i\phi_s}\,\sqrt{\frac{1-C_f}{1+C_f}}\, e^{-i\Delta\phi_f}$$

B^0_s–$\bar{B}^0_s$ Mixing:
M_s, y_s, ϕ_s



Decay Mode:
$\Delta\phi_f,\ C_f$



Tagged CP observable : $\quad \boldsymbol{S_f} = \dfrac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2} = \eta_f\,\sqrt{1-C_f^2}\,\sin(\phi_s + \Delta\phi_f)$

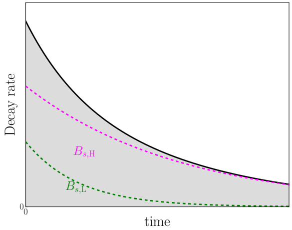
$$\boxed{\mathcal{A}^f_{\Delta\Gamma} = \frac{2\,\mathrm{Re}\,\lambda_f}{1+|\lambda_f|^2} = -\eta_f\,\sqrt{1-C_f^2}\,\cos(\phi_s + \Delta\phi_f)}$$

Probe New Physics with **untagged** time-dependent measurements?

Time-integrated untagged rate

Experiment measures:

$$\overline{\mathrm{BR}}(B_s \to f) \equiv \frac{1}{2}\int \langle \Gamma(B_s(t) \to f\rangle \, dt$$
$$= \frac{1}{2}\left[\frac{\Gamma(B_{s,\mathrm{H}} \to f)}{\Gamma_\mathrm{H}} + \frac{\Gamma(B_{s,\mathrm{L}} \to f)}{\Gamma_\mathrm{L}}\right]$$



Theoretical calculation in flavor basis:

$$\Gamma(B_s^0 \to f) + \Gamma(\bar{B}_s^0 \to f) = \langle \Gamma(B_s(t) \to f)\rangle|_{t=0}$$

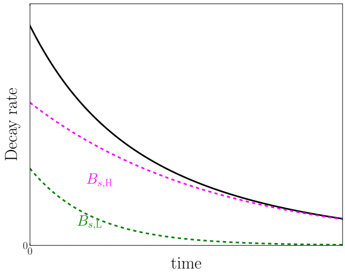
$$\mathrm{BR}(B_s \to f) \equiv \frac{\langle \Gamma(B_s(t) \to f)\rangle|_{t=0}}{\frac{1}{2}(\Gamma_\mathrm{H}+\Gamma_\mathrm{L})} = \frac{1}{2}\left[\frac{\Gamma(B_{s,\mathrm{H}} \to f)}{\frac{1}{2}(\Gamma_\mathrm{H}+\Gamma_\mathrm{L})} + \frac{\Gamma(B_{s,\mathrm{L}} \to f)}{\frac{1}{2}(\Gamma_\mathrm{H}+\Gamma_\mathrm{L})}\right]$$

Dictionary : $$\boxed{\overline{\mathrm{BR}}(B_s \to f) = \mathrm{BR}(B_s \to f)\left[\frac{1 + y_s\,\mathcal{A}^f_{\Delta\Gamma}}{1 - y_s^2}\right]}$$

K. Bruyn, R. Fleischer, RK, P. Koppenburg, M. Merk, N. Tuning, Phys.Rev.D 86 (2012)

The Effective Lifetime

Approximate untagged rate $\langle \Gamma_f \rangle$ with single exponential $\frac{1}{\tau_f} e^{-t/\tau_f}$



Maximum likelihood fit gives:

$$\tau_f = \frac{\int_0^\infty t \, \langle \Gamma_f \rangle \, dt}{\int_0^\infty \langle \Gamma_f \rangle \, dt}$$

$$= \frac{\tau_{B_s}}{1 - {y_s}^2} \left(\frac{1 + 2\, \mathcal{A}^f_{\Delta\Gamma}\, y_s + {y_s}^2}{1 + \mathcal{A}^f_{\Delta\Gamma}\, y_s} \right)$$

Recover theoretical BR:

$$\mathrm{BR}(B_s \to f) = \underbrace{\left[2 - (1 - {y_s}^2) \frac{\tau_f}{\tau_{B_s}} \right] \overline{\mathrm{BR}}(B_s \to f)}_{\text{all measurable quantities}}$$

Contours in the ϕ_s–$\Delta\Gamma_s$ plane

$$\mathcal{CP}|f\rangle = \eta_f|f\rangle \quad \Longrightarrow \quad \mathcal{A}^f_{\Delta\Gamma} = -\eta_f \sqrt{1 - C_f^2}\cos(\phi_s + \Delta\phi_f)$$

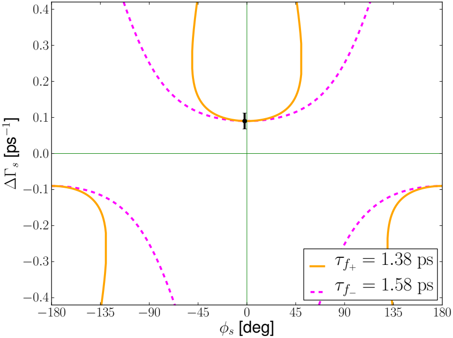
$$\tau_f = \frac{\tau_{B_s}}{1 - {y_s}^2}\left(\frac{1 + 2\,\mathcal{A}^f_{\Delta\Gamma}\, y_s + {y_s}^2}{1 + \mathcal{A}^f_{\Delta\Gamma}\, y_s}\right) = \mathrm{function}(\Delta\Gamma_s,\ \phi_s + \Delta\phi_f,\ C_f)$$

Assuming:

$$\Delta\phi_f = 0,\ \ C_f = 0$$

$$\mathcal{A}^f_{\Delta\Gamma} = \begin{cases} -\cos\phi_s & : \quad f_{\mathrm{even}} \\ +\cos\phi_s & : \quad f_{\mathrm{odd}} \end{cases}$$

(R. Fleischer, RK; 1109.5115)



Measured B_s effective lifetimes

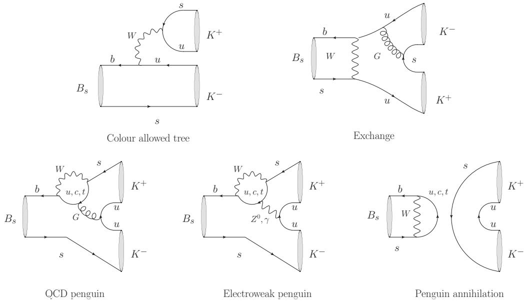
Decay	CP e-val	Effective lifetime	
$B_s \to K^+K^-$	even	$1.455 \pm 0.046 \pm 0.006$ ps	LHCb: 1207.5993
$B_s \to D_s^+ D_s^-$	even	$1.379 \pm 0.026 \pm 0.017$ ps	LHCb: 1312.1217
$B_s \to J/\psi\, f_0(980)$	odd	$1.700 \pm 0.040 \pm 0.026$ ps	LHCb: 1207.0878
$B_s \to J/\psi\, \pi^+\pi^-$	odd	$1.652 \pm 0.024 \pm 0.024$ ps	LHCb: 1304.2600
$B_s \to J/\psi\, K_S$	odd	$1.75 \pm 0.12 \pm 0.07$ ps	LHCb: 1304.4500
$B_s \to J/\psi\, \phi$	mixed	$1.480 \pm 0.011 \pm 0.005$ ps	LHCb: 1402.2554
$B_s \to D^- D_s^+$	n\a	$1.52 \pm 0.15 \pm 0.01$ ps	LHCb: 1312.1217

But...

$$\boxed{\Delta\phi \neq 0, \;\; C \neq 0}$$

...possible CP violation in **Decay Modes**

A closer look at $B_s \to K^+K^-$



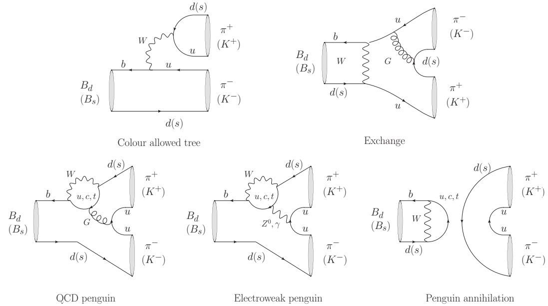
$$A(B_s \to K^+K^-) = \underbrace{V_{us}V_{ub}^*}_{\propto\, \lambda^4\, e^{i\gamma}} \left(A^u_{tree} + A^u_{pen} - A^t_{pen}\right) + \underbrace{V_{cs}V_{cb}^*}_{\propto\, \lambda^2} \left(A^c_{pen} - A^t_{pen}\right)$$

Direct and mixing-induced CPV: (LHCb: 1308.1428)

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^+K^-) = 0.14 \pm 0.11 \pm 0.03$$
$$\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^+K^-) = -0.30 \pm 0.12 \pm 0.04$$

Controlling $B_s \to K^+K^-$ with U-spin symmetry

U-spin symmetry: $s \leftrightarrow d$



1-1 topology mapping to $\boldsymbol{B_d \to \pi^+\pi^-}$ topologies:

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^+\pi^-) = -0.29 \pm 0.05$$
$$\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^+\pi^-) = 0.65 \pm 0.06$$

(HFAG average: Belle, BaBar,LHCb)

U-spin breaking: $f_K/f_\pi - 1$ or $(m_s - m_d)/\Lambda_{\rm QCD} \implies \approx 20\%$

Extraction of γ

$$A(B_d \to \pi^+\pi^-) = \mathcal{C}\,[e^{i\gamma} - d e^{i\theta}] \qquad A(B_s \to K^+K^-) = \sqrt{\epsilon}\,\mathcal{C}'\left[e^{i\gamma} + \frac{1}{\epsilon} d' e^{i\theta'}\right]$$

$$\mathcal{C}^{(\prime)} \equiv A\lambda^3 R_b \left(A_{\rm cc}^{u(\prime)} + A_{\rm pen}^{u(\prime)} - A_{\rm pen}^{t(\prime)}\right), \qquad d^{(\prime)}\, e^{i\theta^{(\prime)}} \equiv \frac{1}{R_b} \frac{A_{\rm pen}^{c(\prime)} - A_{\rm pen}^{t(\prime)}}{A_{\rm cc}^{u(\prime)} + A_{\rm pen}^{u(\prime)} - A_{\rm pen}^{t(\prime)}}.$$

$$\mathcal{A}_{\rm CP}^{\rm dir,mix}(B_d \to \pi^+\pi^-)[d, \theta, \gamma, \phi_d] \quad \xrightarrow{\text{fix } \phi_d} \quad \text{contour in } \gamma\text{–}d \text{ plane}$$

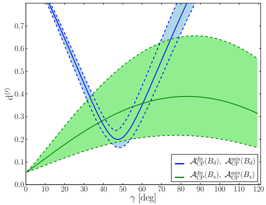
$$\mathcal{A}_{\rm CP}^{\rm dir,mix}(B_s \to K^+K^-)[d', \theta', \gamma, \phi_s] \quad \xrightarrow{\text{fix } \phi_s} \quad \text{contour in } \gamma\text{–}d' \text{ plane}$$

Extract γ from U-spin assumption:

$$d = d'$$

(Fleischer, hep-ph/9903456)

Await more precise $B_s \to K^+K^-$ CP asymmetries



Early determination of γ

$$K \equiv \frac{1}{\epsilon}\left|\frac{\mathcal{C}}{\mathcal{C}'}\right|^2 \left[\frac{M_{B_s}}{M_{B_d}}\,\frac{\Phi(M_\pi/M_{B_d}, M_\pi/M_{B_d})}{\Phi(M_K/M_{B_s}, M_K/M_{B_s})}\,\frac{\tau_{B_d}}{\tau_{B_s}}\right]\frac{\mathbf{BR}(B_s \to K^+K^-)}{\mathbf{BR}(B_d \to \pi^+\pi^-)} = \frac{1}{\epsilon^2}\left[\frac{\epsilon^2 + 2\epsilon d' \cos\theta' \cos\gamma + d'^2}{1 - 2d\cos\theta\cos\gamma + d^2}\right]$$

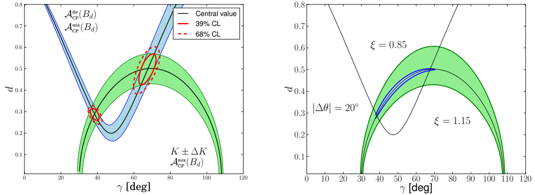
Factorisable U-spin breaking corrections:

$$\left|\frac{\mathcal{C}'}{\mathcal{C}}\right|_{\rm fact} = \frac{f_K}{f_\pi}\,\frac{F_{B_sK}(M_K^2;0^+)}{F_{B_d\pi}(M_\pi^2;0^+)}\left(\frac{M_{B_s}^2 - M_K^2}{M_{B_d}^2 - M_\pi^2}\right) \overset{\rm QCDSR}{=} 1.41^{+0.20}_{-0.11}$$

G.Duplancic, B.Melic; 0805.4170

Parameterise U-spin breaking: $\xi \equiv d/d' = 1 \pm 0.15, \quad \Delta\theta \equiv \theta' - \theta = \pm 20^\circ$

(R. Fleischer, RK; 1011.1096)



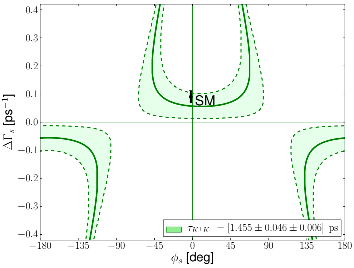
$$\gamma = \left(67.7^{+4.5}_{-5.0}\big|_{\rm input}{}^{+5.0}_{-3.7}\big|_\xi{}^{+0.1}_{-0.2}\big|_{\Delta\theta}\right)^\circ = (68 \pm 7)^\circ$$

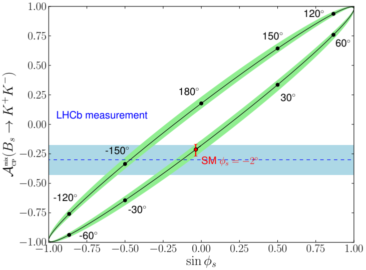
Mixing-induced CPV in $B_s \to K^+K^-$

$$\mathcal{A}_{\Delta\Gamma}(B_s \to K^+K^-) = -\sqrt{1 - C_{K^+K^-}}\,\cos(\phi_s + \Delta\phi_{K^+K^-})$$

$$A_{\rm CP}^{\rm mix}(B_s \to K^+K^-) = \sqrt{1 - C_{K^+K^-}}\,\sin(\phi_s + \Delta\phi_{K^+K^-})$$

$$\Delta\phi_{K^+K^-} = 2\,\epsilon \sin\gamma \left[\frac{d\cos\theta + \epsilon\cos\gamma}{d^2 + 2\epsilon d\cos\theta\cos\gamma + \epsilon^2\cos 2\gamma}\right] = -\left(10.7^{+2.8}_{-2.1}\right)^\circ$$





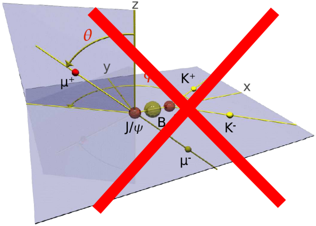
CP even lifetime contour

(R. Fleischer, RK; 1011.1096, 1109.5115)

A closer look at $B_s \to J/\psi\, f_0(980)$

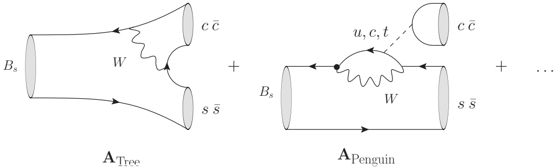
S.Stone, L.Zhang; 0812.2832

$$B_s \to J/\psi\, \not{\phi}\;\; \underbrace{f_0(980)}_{J^{\mathrm{PC}}=0^{++}}$$

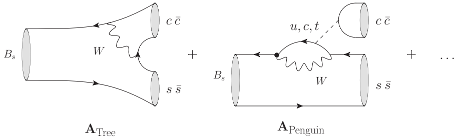


$$\frac{\overline{\mathrm{BR}}(B_s \to J/\psi f_0(980);\, f_0 \to \pi^+\pi^-)}{\overline{\mathrm{BR}}(B_s \to J/\psi\phi;\, \phi \to K^+K^-)} \approx \frac{1}{4}$$

Assuming $\boldsymbol{f_0(980) = s\bar{s}}$ $\to$ also $b \to c\bar{c}s$ transition:



$B_s \to \bar{c}c\bar{s}\,s$



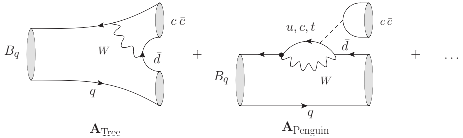
$$A(B_s \to \bar{c}c\bar{s}\,s) = A_{\rm T}\,V_{cb}^*\,V_{cs} + A_{\rm P}^u\,V_{ub}^*\,V_{us} + A_{\rm P}^c\,V_{cb}^*\,V_{cs} + A_{\rm P}^u\,V_{tb}^*\,V_{ts} + \ldots$$

$$= \mathcal{A}\left[1 + \underbrace{\epsilon}_{0.05}\; e^{i\gamma}\; b\, e^{i\theta}\right], \qquad \left(\epsilon \equiv \frac{\lambda^2}{1-\lambda^2}\right)$$

$$\boxed{b\, e^{i\theta} = R_b\left(\frac{A_{\rm P}^u - A_{\rm P}^t}{A_{\rm T} + A_{\rm P}^c - A_{\rm P}^t}\right)}$$

$$\left\{\begin{array}{ll} C & = -2\,\epsilon\, b\, \sin\gamma\, \sin\theta + \mathcal{O}(\epsilon^2) \\ \Delta\phi & = \underbrace{2\,\epsilon}_{6^\circ}\; b\, \sin\gamma\, \cos\theta + \mathcal{O}(\epsilon^2) \end{array}\right.$$

Penguin control via flavour symmetry



$$A(B_q \to \bar{c} c \bar{d}\, q) \stackrel{SU(3)_F}{=} -\lambda\, \mathcal{A} \left[1 - \underbrace{\cancel{\epsilon}}_{1}\, e^{i\gamma}\, b\, e^{i\theta} \right]$$

- Example: $B_d \to J/\psi\, K^0$ to $B_d \to J/\psi\, \pi^0$:

  $b \in [0.15, 0.67], \quad \theta \in [174^\circ, 212^\circ] \quad \Longrightarrow \quad \Delta\phi^d_{J/\psi\, K^0} = [-3.9^\circ, -0.8^\circ]$

  S. Faller, R. Fleischer, M. Jung, T. Mannel, PRD 79 014030 (2009)

  $\Delta S_{B_d \to J/\psi K_s} = 0.00 \pm 0.02 \quad \Longrightarrow \quad \Delta\phi^d_{J/\psi\, K^0} = (0.0 \pm 1.5)^\circ$

  M. Ciuchini, M. Pierini, L. Silvestrini, PRL 95 221804 (2005)/ 1102.0392

- Soon also $B_s \to J/\psi\, K^0$

  K. De Bruyn, R. Fleischer, P. Koppenburg, Eur.Phys.J. C70 (2010) 1025-1035

$B_s \to J/\psi f_0(980)$ - What is the $f_0(980)$?

$f_0(980)$

INSPIRE search

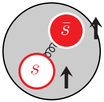
See also the minireview on scalar mesons under $f_0(500)$. (See the index for the page number.)

$f_0(980)$ MASS	990 ± 20 MeV
$f_0(980)$ WIDTH	40 to 1×10^2 MeV

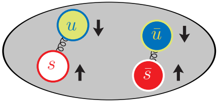
Decay Modes

Γ_i	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Confidence Level	P (MeV/c)
Γ_1	$f_0(980) \to \pi\pi$	dominant		476
Γ_2	$f_0(980) \to K\overline{K}$	seen		36
Γ_3	$f_0(980) \to \gamma\gamma$	seen		495
Γ_4	$f_0(980) \to e^+ e^-$			495

Quark-antiquark



Tetraquark



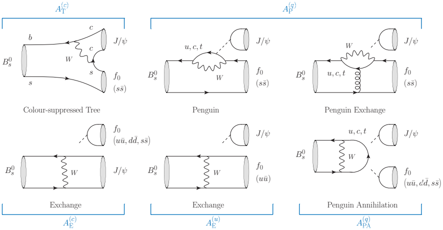
Or a $q\bar{q}$ – tetraquark mixture?

(see G.'t Hooft, G.Isidori, L.Maiani, A.Polosa; 0801.2288)

$f_0(980)$ as quark-antiquark state

$$\begin{pmatrix} |f_0(980)\rangle \\ |f_0(500)\rangle \end{pmatrix} = \begin{pmatrix} \cos\varphi_M & \sin\varphi_M \\ -\sin\varphi_M & \cos\varphi_M \end{pmatrix} \begin{pmatrix} |s\bar{s}\rangle \\ \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right) \end{pmatrix}$$

Mixing phase φ_M largely unconstrained. R.Fleischer, RK, G.Ricciardi; 1109.1112

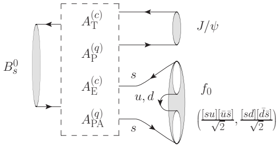


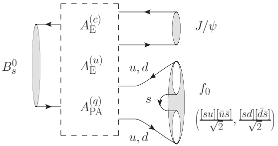
$$be^{i\vartheta}\Big|_{q\bar{q}} = R_b \left[\frac{\cos\varphi_M \left\{ \tilde{A}_{\mathrm{P}}^{(ut)} + \tilde{A}_{\mathrm{PA}}^{(ut)} \right\} + \frac{1}{\sqrt{2}} \sin\varphi_M \left\{ \tilde{A}_{\mathrm{E}}^{(u)} + 2\tilde{A}_{\mathrm{PA}}^{(ut)} \right\}}{\cos\varphi_M \left\{ \tilde{A}_{\mathrm{T}}^{(c)} + \tilde{A}_{\mathrm{P}}^{(ct)} + \tilde{A}_{\mathrm{E}}^{(c)} + \tilde{A}_{\mathrm{PA}}^{(ct)} \right\} + \frac{1}{\sqrt{2}} \sin\varphi_M \left\{ 2\tilde{A}_{\mathrm{E}}^{(c)} + 2\tilde{A}_{\mathrm{PA}}^{(ct)} \right\}} \right].$$

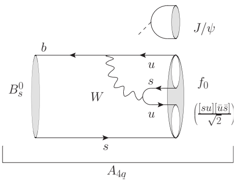
$f_0(980)$ as a tetraquark

$$\begin{pmatrix} |f_0(980)\rangle \\ |f_0(500)\rangle \end{pmatrix} = \begin{pmatrix} \cos\omega & -\sin\omega \\ \sin\omega & \cos\omega \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}}\left([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]\right) \\ [ud][\bar{u}\bar{d}] \end{pmatrix}$$

$|\omega| < 5^\circ$ (see hep-ph/9808415, hep-ph/0407017, 0801.2288)







Ignoring mixing:

$$b e^{i\vartheta}\big|_{\rm 4q} = R_b \left[\frac{\tilde{A}_{\rm P}^{(ut)} + \frac{1}{2}\tilde{A}_{\rm E}^{(u)} + 2\tilde{A}_{\rm PA}^{(ut)} + \frac{1}{2}\tilde{A}_{4q}}{\tilde{A}_{\rm T}^{(c)} + \tilde{A}_{\rm P}^{(ct)} + 2\tilde{A}_{\rm E}^{(c)} + 2\tilde{A}_{\rm PA}^{(ct)}} \right].$$

Proposed control channel: $B_d \to J/\psi f_0(980)$

Driven by $b \to c\bar{c}d \implies$ b'e$^{i\theta'}$ not Cabibbo suppressed

- $q\bar{q}$: exact $SU(3)_{\mathrm{F}}$ correspondence for $\varphi_M = \tan^{-1}\sqrt{2} = 55^\circ$
- in general require: $A_T, A_P \gg A_E, A_{PA}, (A_{4q})$

Decay	Dominant topologies	BR bound
$B_d \to J/\psi\phi$	$A_E^{(c)}$, $A_{PA}^{(ct)}$	$< 9.4 \times 10^{-7}$
$B_s \to J/\psi\pi^0$	$A_E^{(u)}$	$< 1.2 \times 10^{-3}$
$B_s \to J/\psi a^0(980)$	$A_E^{(u)}$, (A_{4q})	

For example

$$\left|\frac{A_{\mathrm{E}}^{(c)} + A_{\mathrm{PA}}^{(ct)}}{A_{\mathrm{T}}^{(c)}}\right| \sim \left(\frac{1-\lambda^2/2}{\lambda}\right)\sqrt{\frac{\mathrm{BR}(B_d \to J/\psi\phi)}{\mathrm{BR}(B_d \to J/\psi K^{*0})}} \lesssim 0.1.$$

R.Fleischer, RK, G.Ricciardi; 1109.1112

Proposed control channel: $B_d \to J/\psi f_0(980)$

Assuming $\gamma = (68 \pm 7)^\circ$ and tree topologies dominant ($b \in [0, 0.5]$):

$$\textbf{Predict}: \quad \mathrm{BR}(B_d \to J/\psi\, f_0; f_0 \to \pi^+\pi^-) \sim (1-3)\times 10^{-6} \times \begin{cases} \left[\frac{\tan\varphi_M}{\tan 35^\circ}\right]^2 & : \quad q\bar{q} \\ 1 & : \quad \mathrm{tetraquark} \end{cases}$$

R.Fleischer, RK, G.Ricciardi; 1109.1112

Experimental bound: (LHCb: 1301.5347)

$$\mathrm{BR}(B_d \to J/\psi\, f_0(980); f_0 \to \pi^+\pi^-) < 1.1 \times 10^{-6}\ (90\%\ \mathrm{C.L})$$

But also: (LHCb: 1402.6248)

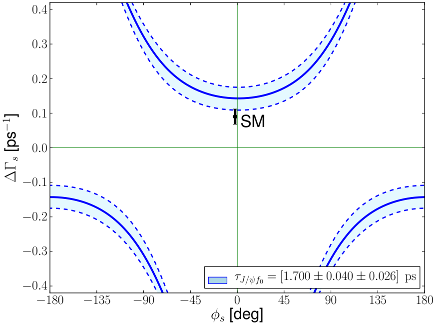
$$\frac{\mathrm{BR}(B_s \to J/\psi\, f_0(500); f_0 \to \pi^+\pi^-)}{\mathrm{BR}(B_s \to J/\psi\, f_0(980); f_0 \to \pi^+\pi^-)} < 3.4\%\ (95\%\ \mathrm{C.L})$$

$$\Longrightarrow \quad \varphi_M < 7.7^\circ$$

$B_s \to J/\psi f_0(980)$ effective lifetime (CP-odd)

Assuming $\gamma = (68 \pm 7)^\circ$ and tree topologies dominant ($b < 0.5$):

$$\boxed{\Delta\phi_{J/\psi f_0} \in [-3^\circ, 3^\circ]} \quad C_{J/\psi f_0} \lesssim 0.05$$



CP odd lifetime contour

A quick look at $B_s \to J/\psi\eta^{(\prime)}$

$$|\eta\rangle = \cos\phi_P \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right) - \sin\phi_P|s\bar{s}\rangle$$

$$|\eta'\rangle = \cos\phi_G \sin\phi_P \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right) + \cos\phi_G\cos\phi_P|s\bar{s}\rangle\rangle + \sin\phi_G|gg\rangle$$

$$30^\circ \lesssim \phi_P \lesssim 45^\circ$$
$$|\phi_G| \sim 20^\circ$$

C. Di Donato, G. Ricciardi, I. Bigi, Phys.Rev. D85 013016 (2012)

A.S. Dighe, M. Gronau, J.L.Rosner, Phys.Lett. B367 (1996) 357-361

Difficult LHC signature: $\eta^{(\prime)} \xrightarrow{\text{prominently}} \gamma, \pi^0$

Belle results:

$$\mathrm{BR}(B_s \to J/\psi\eta) = 5.10^{+1.30}_{-0.97} \times 10^{-4} \qquad \mathrm{BR}(B_d \to J/\psi\eta) = 12.3^{+1.9}_{-1.8} \times 10^{-6}$$

$$\mathrm{BR}(B_s \to J/\psi\eta') = 3.71^{+1.00}_{-0.85} \times 10^{-4} \qquad \mathrm{BR}(B_d \to J/\psi\eta') < 7.4 \times 10^{-6}$$

M. C. Chang et al, Phys. Rev. D85 (2012) 091102, *Belle Collaboration, Phys. Rev. Lett. 108 (2012) 181808*

Determining the $\eta^{(\prime)}$ mixing angles

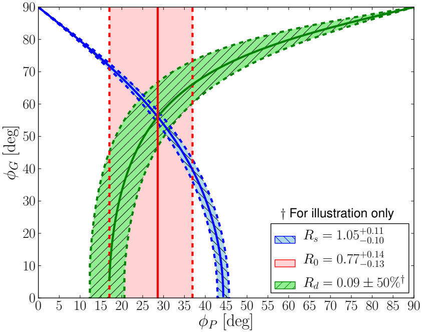
Assuming $A_{\mathrm{T}}, A_{\mathrm{P}} \gg A_{\mathrm{E}}, A_{\mathrm{PA}}$:

$$R_s \equiv \frac{\mathrm{BR}(B_s \to J/\psi\eta')}{\mathrm{BR}(B_s \to J/\psi\eta)} \left(\frac{\Phi_s^\eta}{\Phi_s^{\eta'}}\right)^3 = \frac{\cos^2\phi_G}{\tan^2\phi_P} = 0.91 \pm 0.18$$

$$R_0 \equiv \frac{\mathrm{BR}(B_d \to J/\psi\eta)}{\mathrm{BR}(B_d \to J/\psi\pi^0)} \left(\frac{\Phi_d^\pi}{\Phi_d^{\eta}}\right)^3 = \cos^2\phi_P = 0.77 \pm 0.14$$

$$R_d \equiv \frac{\mathrm{BR}(B_d \to J/\psi\eta')}{\mathrm{BR}(B_d \to J/\psi\eta)} \left(\frac{\Phi_d^\eta}{\Phi_d^{\eta'}}\right)^3 = \cos^2\phi_G \tan^2\phi_P = \mathbf{??}$$

Φ_q^P : phase space

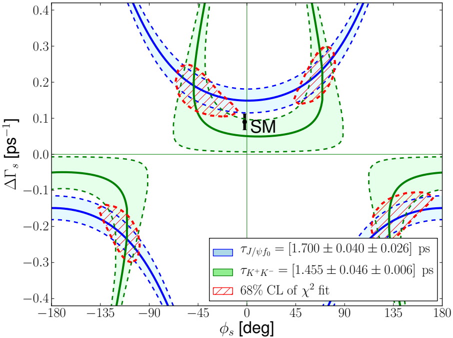


R.Fleischer, RK, G.Ricciardi; 1110.5490

Lifetime contours in the ϕ_s–$\Delta\Gamma_s$ plane

$$\tau_f = \text{function}\left(\Delta\Gamma_s,\ \boxed{\phi_s + \Delta\phi},\ C\right)$$

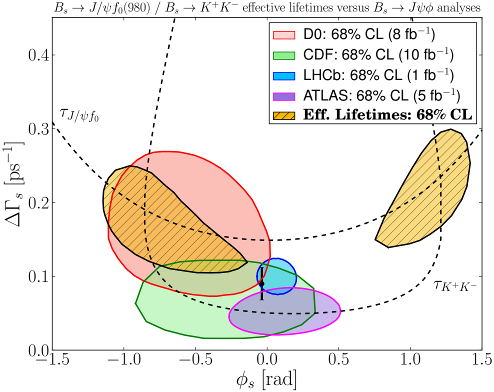
- **CP Even :** $\tau_{K^+K^-}$, $\Delta\phi_{K^+K^-} = -\left(10.5^{+3.1}_{-2.8}\right)^\circ$, $C_{K^+K^-} = 0.09$
- **CP Odd :** $\tau_{J/\psi\, f_0}$, $\Delta\phi_{J/\psi\, f_0} \in [-3^\circ, 3^\circ]$, $C_{J/\psi\, f_0} \leq 0.05$

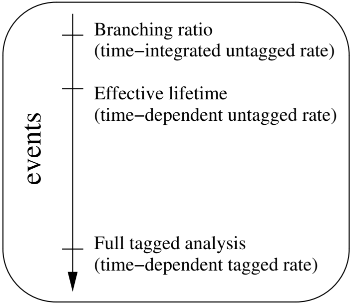


R. Fleischer and RK, Eur.Phys.J. C71 (2011) 1532, *RK, C12-06-11.2; 1209.3206*

Comparison with tagged measurements

Full tagged $B_s \to J/\psi\phi$ analysis:





Upcoming *untagged time-dependent* measurements?

The Rare Decay $B_s \to \mu^+\mu^-$

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) = \begin{cases} (2.9^{+1.1}_{-1.0}) \times 10^{-9} & \mathrm{LHCb} \\ (3.0^{+1.0}_{-0.9}) \times 10^{-9} & \mathrm{CMS} \end{cases} = (2.9 \pm 0.7) \times 10^{-9}$$

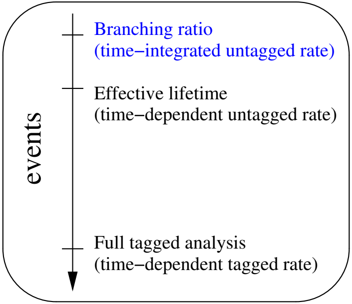
LHCb: Phys.Rev.Lett. 111 (2013) 101805, CMS: Phys.Rev.Lett. 111 (2013) 101804

To be compared with:

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$

Includes:

- NLO EW and NNLO QCD effects
  C.Bobeth, M.Gorbahn, T. Hermann, M.Misiak, E.Stamou, M.Steinhauser; Phys.Rev.Lett. 112 (2014) 101801
- y_s effect $(\mathcal{A}^{\mu\mu}_{\Delta\Gamma}|_{\mathrm{SM}} = 1)$
  K. Bruyn, R. Fleischer, RK, P. Koppenburg, M. Merk, A. Pellegrino, N. Tuning, Phys.Rev.Lett 109 (2012)

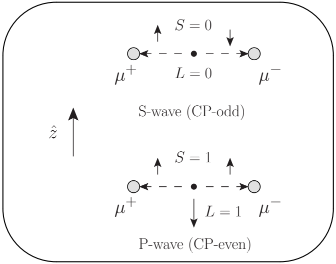


$$\overline{R} \equiv \frac{\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)}{\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}},$$

$$\boxed{\overline{R}_{\mathrm{LHCb}} = 0.79 \pm 0.20, \qquad \overline{R}_{\mathrm{SM}} = 1}$$

$B_s \to \mu^+\mu^-$ beyond the Standard Model

$$\mathcal{H}_{\text{eff}} = -\frac{G_F\,\alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \sum_i^{\{10,S,P\}} \left(C_i\,\mathcal{O}_i + C_i'\,\mathcal{O}_i' \right)$$

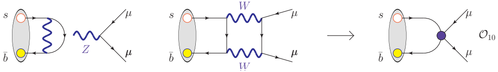


$$\boldsymbol{\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu\gamma_5\mu)}$$

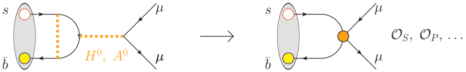
$$\mathcal{O}_S = (\bar{s}P_R b)(\bar{\mu}\mu)$$

$$\mathcal{O}_P = (\bar{s}P_R b)(\bar{\mu}\gamma_5\mu) \qquad (P_L \leftrightarrow P_R \text{ for } \mathcal{O}')$$

Standard Model: only $\boldsymbol{\mathcal{O}_{10}}$ $\Longrightarrow$ only $\boldsymbol{B_{s,\mathrm{H}}} \to \mu^+\mu^-$



Beyond the SM: non-vanishing $\boldsymbol{B_{s,\mathrm{L}}} \to \mu^+\mu^-$?



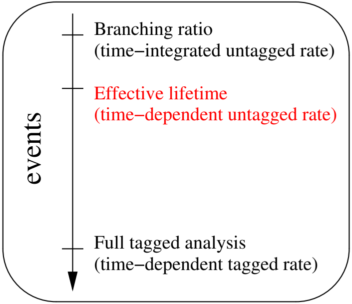
$B_s \to \mu^+\mu^-$ time-dependent measurement

Define for convenience:

$$\boldsymbol{P} \equiv \frac{C_{10} - C'_{10}}{C_{10}^{\rm SM}} + \frac{m_{B_s}}{2\, m_\mu}\left(\frac{C_P - C'_P}{C_{10}^{\rm SM}}\right)$$

$$\boldsymbol{S} \equiv \sqrt{1 - \frac{4\, m_\mu^2}{m_{B_s}^2}}\,\frac{m_{B_s}}{2\, m_\mu}\left(\frac{C_S - C'_S}{C_{10}^{\rm SM}}\right)$$

In SM: $\boldsymbol{P} \to 1$, $\boldsymbol{S} \to 0$

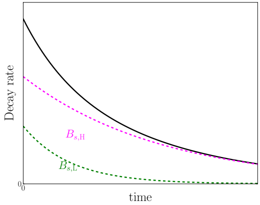


$$\Gamma(\boldsymbol{B}_{\boldsymbol{s},\rm L} \to \mu^+\mu^-) \propto |\boldsymbol{P}|^2 \underbrace{\sin^2(\varphi_{\boldsymbol{P}} - \phi_s^{\rm NP}/2)}_{\text{new CP phases}} + \underbrace{|\boldsymbol{S}|^2 \cos^2(\varphi_{\boldsymbol{S}} - \phi_s^{\rm NP}/2)}_{\text{scalar operators}}$$

$$\text{Probe } \textbf{NP} \text{ with :} \quad \mathcal{A}_{\Delta\Gamma}^{\mu\mu} \equiv \frac{\Gamma(B_{s,\rm H} \to \mu^+\mu^-) - \Gamma(B_{s,\rm L} \to \mu^+\mu^-)}{\Gamma(B_{s,\rm H} \to \mu^+\mu^-) + \Gamma(B_{s,\rm L} \to \mu^+\mu^-)}$$

e.g. with $B_s \to \mu^+\mu^-$ Effective Lifetime

$B_s \to \mu^+\mu^-$ untagged observables



$$\overline{R} = \frac{\left(1 + y_s\, \mathcal{A}^{\mu\mu}_{\Delta\Gamma}\right)}{1 + y_s} \left(|\boldsymbol{P}|^2 + |\boldsymbol{S}|^2\right)$$

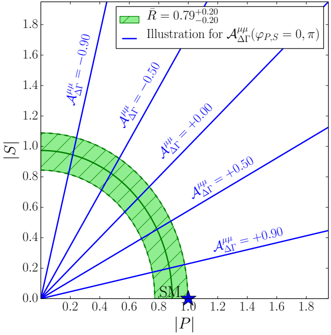
$$\mathcal{A}^{\mu\mu}_{\Delta\Gamma} = \frac{|\boldsymbol{P}|^2 \cos\left(2\varphi_{\boldsymbol{P}} - \phi_s^{\mathrm{NP}}\right) - |\boldsymbol{S}|^2 \cos\left(2\varphi_{\boldsymbol{S}} - \phi_s^{\mathrm{NP}}\right)}{|\boldsymbol{P}|^2 + |\boldsymbol{S}|^2}$$

K. Bruyn, R. Fleischer, RK, P. Koppenburg, M. Merk, A. Pellegrino, N. Tuning, Phys.Rev.Lett 109 (2012)

Solvable scenarios:

- A: $|\boldsymbol{P}|$, $\varphi_{\boldsymbol{P}}$ free ($\boldsymbol{S} = 0$)
- B: $|\boldsymbol{S}|$, $\varphi_{\boldsymbol{S}}$ free ($\boldsymbol{P} = 1$)
- C: $\boldsymbol{S} = \pm[1 - \boldsymbol{P}]$
- D: $\varphi_{\boldsymbol{P}} = \varphi_{\boldsymbol{S}} = 0$: $\longrightarrow$

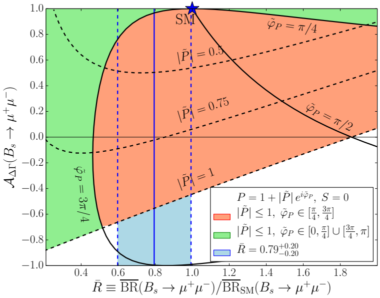
A.J. Buras, R. Fleischer, J. Girrbach, RK, JHEP 1307 (2013) 77



No scalar operators || only new scalar operators

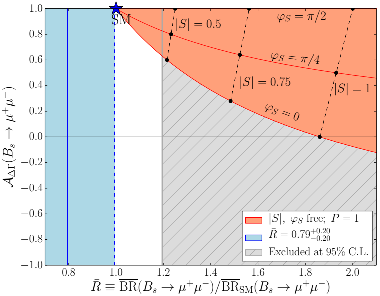
$$\Gamma(\boldsymbol{B_{s,\mathrm{L}}} \to \mu^+\mu^-) \propto |\boldsymbol{P}|^2 \underbrace{\sin^2(\varphi_{\boldsymbol{P}} - \phi_s^{\mathrm{NP}}/2)}_{\text{scenario A}} + \underbrace{|\boldsymbol{S}|^2 \cos^2(\varphi_{\boldsymbol{S}} - \phi_s^{\mathrm{NP}}/2)}_{\text{scenario B}}$$

Scenario A: $\boldsymbol{S = 0}$



E.g: CMFV, Z' Models, A^0 dominant (2HDM)

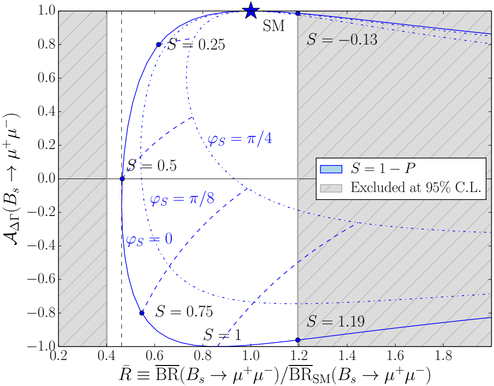
Scenario B: $\boldsymbol{S \neq 0}$ ($P = 1$)



E.g: H^0 dominant (2HDM)

New scalar and pseudoscalar operators on same footing

Scenario C: $P = 1 + \tilde{P}$, $\boldsymbol{S = \pm\tilde{P}}$



Realised for:

$$C_S^{(\prime)} = \pm C_P^{(\prime)}$$

Example

2HDM in decoupling regime:

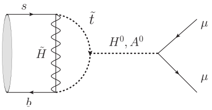
$M_{H^0} \simeq M_{A^0} \simeq M_{H^\pm} \gg M_{h^0}$

$C_S \simeq -C_P$

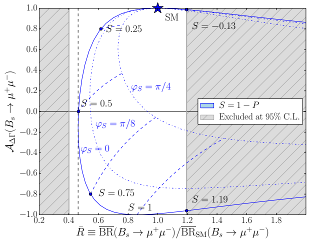
$\left(\simeq \frac{m_b}{m_s} C_S' \simeq \frac{m_b}{m_s} C_P'\right)$ (MFV)

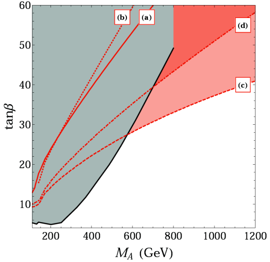
- Full range of $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ without CP violating phases
- Lower bound $\overline{R} \geq (1 - y_s)/2$

The MSSM with large tan β



$$C_S \simeq -C_P \approx \frac{m_\mu m_b}{8\pi\,\alpha}\,\frac{\tan^3\beta}{M_A^2}\,\frac{\mu A_t}{M_{\tilde{t}_L^2}} \qquad \text{(MFV)}$$



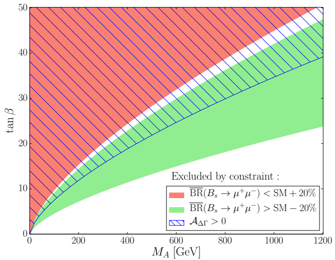


Altmannshofer et al.; 1211.1976, 1306.0022

(a) $\mu = 1$ TeV, $A_t > 0$ (destructive interference)

(c) $\mu = -1.5$ TeV, $A_t > 0$ (constructive interference)

$\tilde{M}_q = 2$ TeV, $|A_t|$ tuned s.t. $M_h = 126\,\mathrm{GeV}$



Example of destructive interference scenario

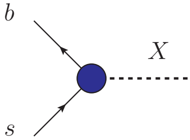
Loose bound on $\mathcal{A}_{\Delta\Gamma}$ can rule out "large tan β" allowed regions

Compatibility with B_s mixing constraints

Consider generic models:

$$X \in \{ \quad \boldsymbol{Z'}, \quad \boldsymbol{H^0}, \quad \boldsymbol{A^0}, \quad \boldsymbol{H^0 + A^0} \quad \},$$

$$M_X = 1\,\mathrm{TeV}$$



$$\mathcal{L}_{\mathsf{FCNC}}(Z') = \left[\Delta_L^{sb}(Z')\,\bar{s}\gamma_\mu P_L b + \Delta_R^{sb}(Z')\,\bar{s}\gamma_\mu P_R b\right] Z'^{\mu}$$
$$\mathcal{L}_{\mathsf{FCNC}}(H) = \left[\Delta_L^{sb}(H)\,\bar{s} P_L b + \Delta_R^{sb}(H)\,\bar{s} P_R b\right] H$$

A.J. Buras, F. De Fazio, J. Girrbach, JHEP 1302 (2013) 116

A.J. Buras, F. De Fazio, J. Girrbach, RK, M. Nagai, JHEP 1306 (2013) 111

Including $\Delta F = 2$ NLO corrections: *A.J. Buras, J. Girrbach, JHEP 1203 (2012) 052*

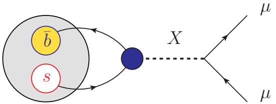
- Apply B_s mixing constraints:

$$\Delta M_s \in \Delta M_{s,\mathrm{exp}}^{\mathrm{cent.\ val.}} \pm 5\%, \qquad \phi_s \in \phi_{s,\mathrm{exp}}^{\mathrm{cent.\ val.}} \pm 2\,\sigma$$

Specific models in the $\overline{R}$-$\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ parameter space

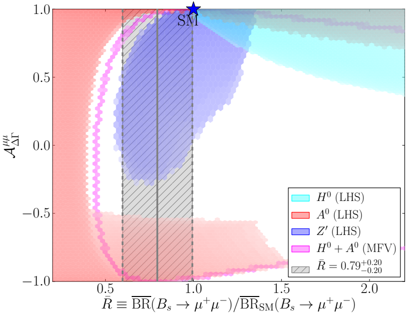
$$X \in \{ \quad \boldsymbol{Z'}, \quad \boldsymbol{H^0}, \quad \boldsymbol{A^0}, \quad \boldsymbol{H^0} + \boldsymbol{A^0} \quad \},$$

$$M_X = 1\,\mathrm{TeV}$$



- B_s mixing (ΔM_s, ϕ_s) constrains quark couplings
- Lepton couplings left free (no CPV)
- Z' includes combined $b \to s\ell\ell$ constraints on C_{10}

W.Altmannshofer, D.Straub; 1206.0273



A.J. Buras, R. Fleischer, J. Girrbach, RK, JHEP 1307 (2013) 77

A.J. Buras, F. De Fazio, J. Girrbach, RK, M. Nagai, JHEP 1306 (2013) 111

$B_s \to \mu^+\mu^-$ tagged analysis

Eventually also tagged measurement:

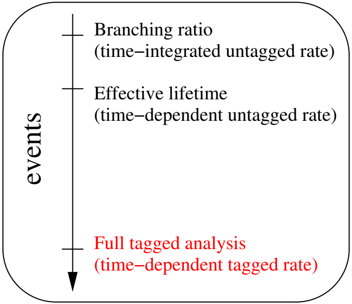
$$\frac{\Gamma(B_s^0(t) \to \mu^+\mu^-) - \Gamma(\bar{B}_s^0(t) \to \mu^+\mu^-)}{\Gamma(B_s^0(t) \to \mu^+\mu^-) + \Gamma(\bar{B}_s^0(t) \to \mu^+\mu^-)} = \frac{\boldsymbol{\mathcal{S}_{\mu\mu}} \sin(\Delta M_s t)}{\cosh(y_s t/\tau_{B_s}) + \boldsymbol{\mathcal{A}_{\Delta\Gamma}^{\mu\mu}} \sinh(y_s t/\tau_{B_s})}.$$

- $\mathcal{S}_{\mu\mu}$ **indepedent** if scalar operators:

$$|\boldsymbol{\mathcal{A}_{\Delta\Gamma}^{\mu\mu}}|^2 + |\boldsymbol{\mathcal{S}_{\mu\mu}}|^2 = 1 - \left[\frac{2|P||S|\cos(\varphi_P - \varphi_S)}{|P|^2 + |S|^2}\right]^2$$

- $\mathcal{S}_{\mu\mu}$ sensitive to small CP phases:

$$\boldsymbol{\mathcal{S}_{\mu\mu}} = \frac{|P|^2 \sin(2\varphi_P - \phi_s^{\mathrm{NP}}) - |S|^2 \sin(2\varphi_S - \phi_s^{\mathrm{NP}})}{|P|^2 + |S|^2}$$



Summary

- No **smoking gun signal of NP** $\Longrightarrow$ smallish NP?
  complementary strategies to flagship analyses desirable!

- Sizable B_s width difference ($y_s \approx 7\%$) allows extraction of **mass-eigenstate rate asymmetries** $\left(\mathcal{A}^f_{\Delta\Gamma}\right)$ from time-dependent untagged measurements

  e.g. **effective lifetimes**

  important ingredient for: $\mathrm{BR}(B_s \to f) \overset{\mathcal{A}^f_{\Delta\Gamma}/\tau_f}{\longleftrightarrow} \overline{\mathrm{BR}}(B_s \to f)$

- Probe B^0_s–$\bar{B}^0_s$ mixing parameters from pair of effective lifetimes $(\tau_{f_+},\ \tau_{f_-})$,
- Effective lifetime of $B_s \to \mu^+\mu^-$ complements branching ratio for searching for NP (particularly for new scalars!)

Backup slides

Fitting an effective lifetime

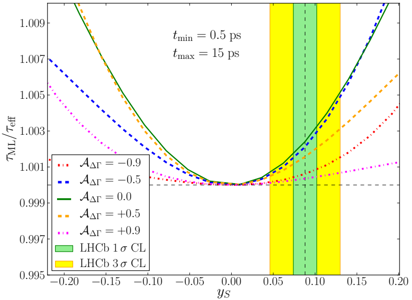
$$f_{\rm true}(t) \equiv \frac{A(t)\,\langle\Gamma(t)\rangle}{\int_0^\infty A(t)\,\langle\Gamma(t)\rangle\,dt}, \qquad f_{\rm fit}(t;\tau) \equiv \frac{A(t)\,e^{-t/\tau}}{\int_0^\infty A(t)\,e^{-t/\tau}\,dt}$$

Minimise : $$-\log L(\tau) = -n\int_0^\infty dt\;f_{\rm true}(t)\log\left[f_{\rm fit}(t;\tau)\right]$$

$$\frac{\int_0^\infty t\,A(t)e^{-t/\tau}\,dt}{\int_0^\infty A(t)e^{-t/\tau}\,dt} = \frac{\int_0^\infty t\,A(t)\langle\Gamma(t)\rangle dt}{\int_0^\infty A(t)\langle\Gamma(t)\rangle dt}$$

Limit that $A(t) = 1$:

$$\tau = \frac{\int_0^\infty t\,\langle\Gamma(t)\rangle dt}{\int_0^\infty \langle\Gamma(t)\rangle dt} \equiv \tau_{\rm eff},$$



Tetraquarks

- diquark–antidiquark (colour) bound states

$$\sigma = [ud][\bar{u}\bar{d}]$$
$$\kappa = [su][\bar{u}\bar{d}]; [sd][\bar{u}\bar{d}] \quad (+\mathrm{c.d})$$
$$f_0 = \frac{[su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]}{\sqrt{2}}$$
$$a_0 = [su][\bar{s}\bar{d}]; \frac{[su][\bar{s}\bar{u}] - [sd][\bar{s}\bar{d}]}{\sqrt{2}}; [sd][\bar{s}\bar{u}]$$

$$\boxed{\text{diquark} \equiv [q_1\, q_2],\ \text{colour } \bar{\mathbf{3}},\ \text{flavour } \bar{\mathbf{3}},\ S = 0}$$

- Issues: $f_0 \to \pi\pi$ coupling too small, $a_0 \to \eta\pi$ too large.
- Solved by adding *instanton-induced effects*

A Theory of Scalar Mesons, G. 't Hooft, G. Isidori, A.D Polosa, V. Riquer,

(arXiv:0801.2288)

Tagged analysis

The CP asymmetry:

$$\frac{\Gamma\,(B_s(t)\to f) - \Gamma(\bar{B}_s(t)\to f)}{\Gamma(B_s(t)\to f) + \Gamma(\bar{B}_s(t)\to f)} = \frac{C\cos(\Delta M_s\,t) + S\,\sin(\Delta M_s\,t)}{\cosh(\Delta\Gamma_s\,t) + \mathcal{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_s\,t)}$$

Observables for $\mathcal{CP}|f\rangle = \eta\,|f\rangle$:

$$\lambda_f \equiv \frac{q}{p}\;\frac{A(\overline{B}_s^0\to f)}{A(B_s^0\to f)} = -\eta\; e^{-i\phi_s}\;\sqrt{\frac{1-C}{1+C}}\,e^{-i\Delta\phi}$$

$$\mathcal{A}_{\Delta\Gamma} + i\,S = \frac{2\;\lambda_f}{1+|\lambda_f|^2} = \boxed{-\eta\,\sqrt{1-C^2}\;e^{-i(\phi_s+\Delta\phi)}}$$