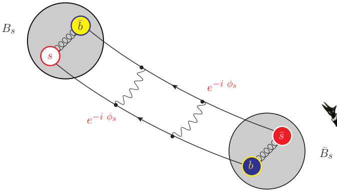
Phenomenology with a non-zero B_s lifetime difference

Rob Knegjens

B_s mass eigenstates

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



Oscillate before decaying

"Normal" modes

Mass basis: $\mathbf{B_{s,H}}$, $\mathbf{B_{s,L}}$

$$\left| \mathbf{B}_{\substack{\mathbf{H}\\ \mathbf{L}}} \right\rangle = p|\mathbf{B^0}\rangle \pm q|\mathbf{\bar{B}^0}\rangle, \qquad \frac{q}{p} = -e^{-i\,\phi_s}$$

(assuming $|q/p| = 1$
i.e. no CPV in mixing)

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

B_s decay width difference

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

$$K_{\mathrm{S}} \approx K_+ \to \pi\pi \qquad \mathbf{B_{s,+}} \to D_s^{(*)}\bar{D}_s^{(*)}, \ldots$$

$$y_K = \frac{\Gamma_{\mathrm{L}} - \Gamma_{\mathrm{S}}}{\Gamma_{\mathrm{L}} + \Gamma_{\mathrm{S}}} \approx -1 \quad \overset{\text{analogously}}{\Longrightarrow} \quad \boxed{\mathbf{y_s} \equiv \frac{\Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{L}} + \Gamma_{\mathrm{H}}} = ?}$$

In Standard Model expect $\phi_s \approx -2^\circ$:

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

$$\mathbf{y_s}|_{\mathrm{SM}} = \begin{cases} 0.067 \pm 0.016 \\ 0.074 \pm 0.007 \end{cases}$$

A. Lenz, U. Nierste, arXiv:1102.4274

Talk of L. Silvestrini

Indeed non-vanishing: *LHCb collaboration, arXiv:1304.2600*

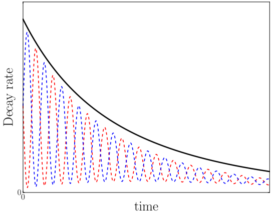
$$\text{LHCb } B_s \to J/\psi\,\phi \text{ analysis :} \quad \boxed{\mathbf{y_s}|_{\mathrm{LHCb}} = 0.075 \pm 0.012}$$

See talks of F. Dupertuis and C. Heller

The untagged decay rate

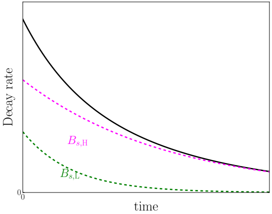
$$\langle \Gamma(B_s(t) \to f) \rangle = \frac{1}{N_{B_s}} \frac{dN_e(B_s \to f)}{dt} = \dots$$

Flavour basis



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

Mass e-state basis



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

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

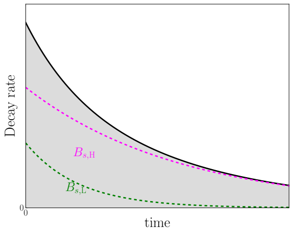
$$\boxed{\mathcal{A}^{\mathbf{f}}_{\mathbf{\Delta\Gamma}} = \frac{\Gamma(B_{s,\mathrm{H}} \to f) - \Gamma(B_{s,\mathrm{L}} \to f)}{\Gamma(B_{s,\mathrm{H}} \to f) + \Gamma(B_{s,\mathrm{L}} \to f)}} \qquad \text{(a.k.a } D_f\text{)}$$

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:

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

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

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

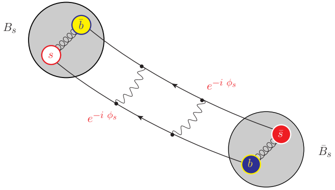
K. Bruyn, R. Fleischer, RK, P. Koppenburg, M. Merk, N. Tuning, Phys.Rev.D 86 (2012)

$\mathcal{A}^{\mathbf{f}}_{\mathbf{\Delta\Gamma}}$: mass eigenstate rate asymmetry

- Final state dependent, sensitive to New Physics

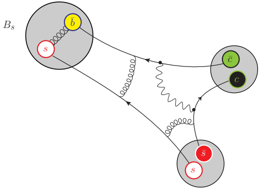
Consider: $B_s \to f$ with $\mathcal{CP}|f\rangle = \eta_f |f\rangle$

B_s^0–$\bar{B}_s^0$ Mixing



y_s, ϕ_s

Decay Mode



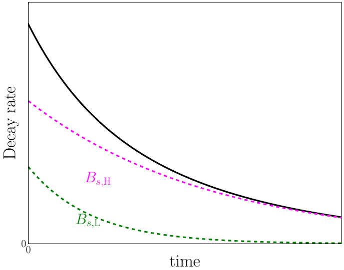
$\Delta\phi_f$, C_f (direct CPV)

$$\mathcal{A}^{\mathbf{f}}_{\mathbf{\Delta\Gamma}} = -\eta_f \sqrt{1 - C_f^2}\,\cos(\phi_s + \Delta\phi_f)$$

Probe NP with **untagged** time-dependent measurements?

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

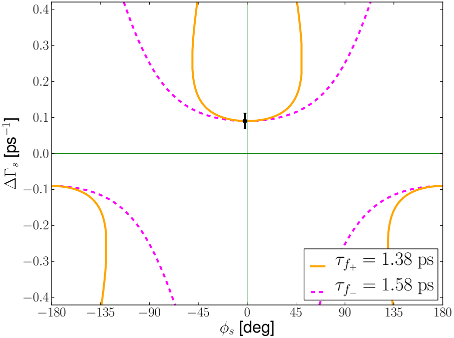
$$\mathcal{CP}|f\rangle = \eta_f |f\rangle \quad \Longrightarrow \quad \mathcal{A}^{\mathbf{f}}_{\mathbf{\Delta\Gamma}} = -\eta_f \sqrt{1 - C_f^2}\, \cos(\phi_s + \Delta\phi_f)$$

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

Assuming:

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

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



Measured Effective Lifetimes

Final state:

- CP Even $B_s \to K^+K^-$: *LHCB, arXiv:1207.5993*

$$\tau_{K^+K^-} = [1.455 \pm 0.046 \pm 0.006]\ \mathrm{ps}$$

(see talk of A. Martens)

- CP Odd $B_s \to J/\psi f_0(980)$: *LHCb, arXiv:1207.0878*

$$\tau_{J/\psi f_0} = [1.700 \pm 0.040 \pm 0.026]\ \mathrm{ps}$$

$\tau_{J/\psi\pi^+\pi^-}$ *update in arXiv:1304.2600 (see talk of F. Dupertuis)*

- CP Odd $B_s \to J/\psi K_S$: *LHCb, S. Playfer's talk*

$$\tau_{J/\psi K_S} = [1.75 \pm 0.12 \pm 0.07]\ \mathrm{ps}$$

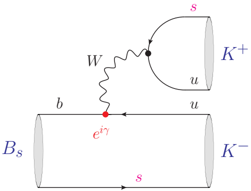
But...

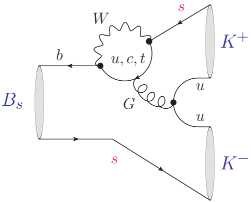
$$\boxed{\Delta\phi \neq 0,\ \ C \neq 0}$$

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

Controlling the **CP Even** Decay Mode

$$B_s \to K^+ K^-$$





$$\Delta\phi_{K^+K^-} = -\left(10.5^{+3.1}_{-2.8}\right)^\circ$$

$$C_{K^+K^-} = 0.09 \pm 0.05$$

- Use *U*-**spin** flavour symmetry (subgroup $SU(3)_F$):

R. Fleischer, Phys.Lett.B 459 (1999) 306

interchange $s \leftrightarrow d$ quarks — Related to $B_d \to \pi^+\pi^-$

Extract **CP violating phase**:

$$\gamma = \left(68^{+5}_{-6}\Big|_{\rm input}{}^{+5}_{-4}\Big|_{\rm U-spin}\right)^\circ = (68 \pm 7)^\circ$$

R. Fleischer and RK, Eur.Phys.J. C71 (2011) 1532

Controlling the **CP Odd** Decay Mode

$$B_s \to J/\psi\, f_0(980)$$

$f_0(980)$ [a]	$I^G(J^{PC}) = 0^+(0^{++})$	$f_0(980)$ Section References

See also the minireview on scalar mesons .

Mass m = (980 ± 10) MeV
Full width Γ = 40 to 100 MeV

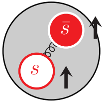
$f_0(980)$ DECAY MODES

Γ_i	Mode	Fraction (Γ_i / Γ)	p (MeV/c)
Γ_1	$\pi\,\pi$	dominant	471
Γ_2	$K\,\overline{K}$	seen	-1
Γ_3	$\gamma\,\gamma$	seen	490
Γ_4	$e^+\,e^-$		490

Controlling the **CP Odd** Decay Mode

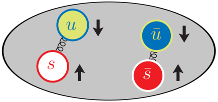
$$B_s \to J/\psi\, f_0(980)$$

Quark-antiquark

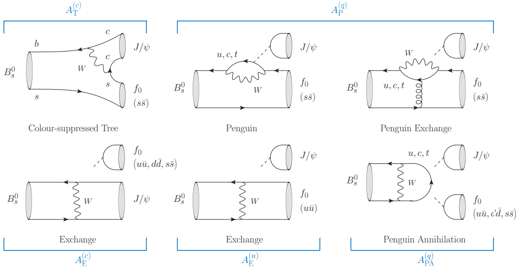


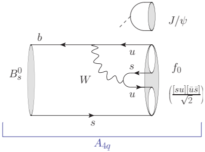
What is $f_0(980)$?

Tetraquark



- Decay amplitudes may vary:





Controlling the **CP Odd** Decay Mode

- With SM CP violation and **unknown decay amplitudes**:

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

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

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, Eur.Phys.J. C71 (2011) 1832

So far:

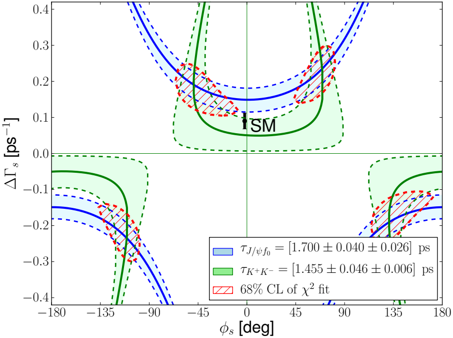
$$\mathrm{BR}(B_d \to J/\psi\, f_0; f_0 \to \pi^+\pi^-)_{\mathrm{LHCb}} < 1.1 \times 10^{-6} \ (90\% \ \mathrm{C.L})$$

LHCb, Phys. Rev. D87 (2013) 052001

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 :** $\tau_{J/\psi\, f_0}$, $\Delta\phi_{J/\psi\, f_0} \in [-3^\circ, 3^\circ]$, $C_{J/\psi\, f_0} \leq 0.05$

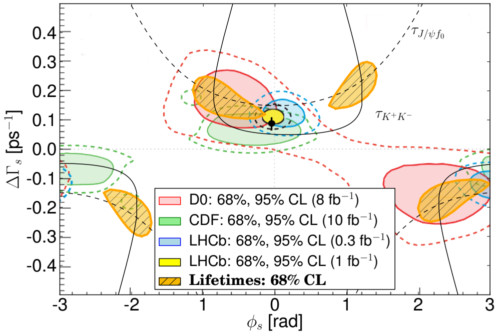


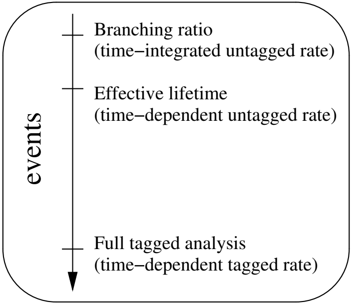
R. Fleischer and RK, Eur.Phys.J. C71 (2011) 1532

RK, C12-06-11.2, arXiv:1209.3206

Comparison with tagged measurements

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





Decays where *untagged time-dependent* measurements upcoming?

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

Hot topic: had it's own session at this conference!

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{LHCb}} = (3.2^{+1.5}_{-1.2})\times 10^{-9}$$

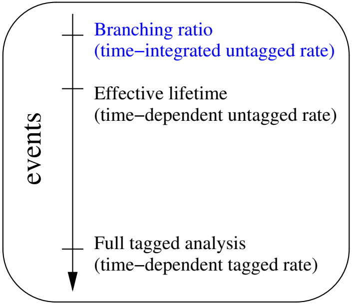
LHCb, Phys.Rev.Lett. 110 (2013) 021801

- Standard Model: **only** $B_{s,\mathrm{H}} \to \mu^+\mu^-$
- Including y_s effects with $\mathcal{A}^{\mu\mu}_{\Delta\Gamma}|_{\mathrm{SM}} = 1$:

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.56 \pm 0.18)\times 10^{-9}$$

A.J. Buras, J. Girrbach, D. Guadagnoli, G. Isidori, Eur.Phys.J. C72 (2012) 2172

A.J. Buras, R. Fleischer, J. Girrbach, RK, arXiv:1303.3820



For convenience define:

$$\overline{R} \equiv \frac{\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)}{\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}}, \qquad \boxed{\overline{R}_{\mathrm{LHCb}} = 0.90^{+0.42}_{-0.34}, \qquad \overline{R}_{\mathrm{SM}} = 1}$$

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

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

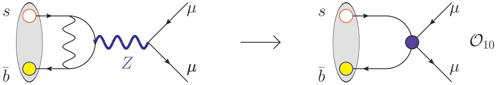
See W. Altmannshofer's talk

$$\mathcal{H}_{\rm eff} \propto \sum_i^{\{10,S,P\}} C_i\,\mathcal{O}_i + C_i'\,\mathcal{O}_i'$$

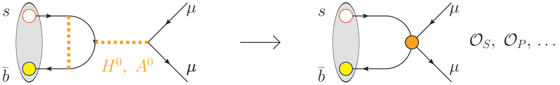
$$\boldsymbol{\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu\gamma_5\mu)}$$
$$\mathcal{O}_S = (\bar{s}P_R b)(\bar{\mu}\mu)$$
$$\mathcal{O}_P = (\bar{s}P_R b)(\bar{\mu}\gamma_5\mu)$$

(and $P_L \leftrightarrow P_R$ for $\mathcal{O}'$)

In Standard Model only $\boldsymbol{\mathcal{O}_{10}} \implies$ only $\mathbf{B_{s,H}} \to \mu^+\mu^-$



Beyond the SM:



Non-vanishing $\mathbf{B_{s,L}} \to \mu^+\mu^-$?

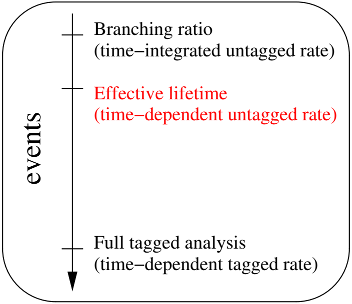
$B_s \to \mu^+\mu^-$ time-dependent measurement

Define for convenience:

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

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

In SM: $P \to 1$, $S \to 0$

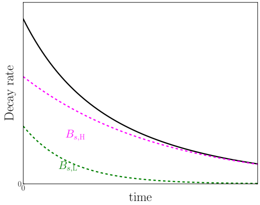


$$\Gamma(\mathbf{B_{s,L}} \to \mu^+\mu^-) \propto |\mathbf{P}|^2 \underbrace{\sin^2(\varphi_{\mathbf{P}} - \phi_s^{\rm NP}/2)}_{\text{new CP phases}} + \underbrace{|\mathbf{S}|^2 \cos^2(\varphi_{\mathbf{S}} - \phi_s^{\rm NP}/2)}_{\text{scalar operators}}$$

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

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

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



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

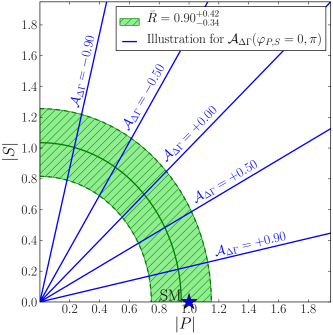
$$\mathcal{A}_{\Delta\Gamma}^{\mu\mu} = \frac{|\mathbf{P}|^2\cos\left(2\varphi_{\mathbf{P}} - \phi_s^{\mathrm{NP}}\right) - |\mathbf{S}|^2\cos\left(2\varphi_{\mathbf{S}} - \phi_s^{\mathrm{NP}}\right)}{|\mathbf{P}|^2 + |\mathbf{S}|^2}$$

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

Solvable scenarios:

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

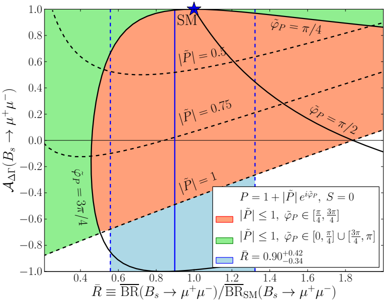
A.J. Buras, R. Fleischer, J. Girrbach, RK, arXiv:1303.3820



No scalar operators OR only new scalar operators

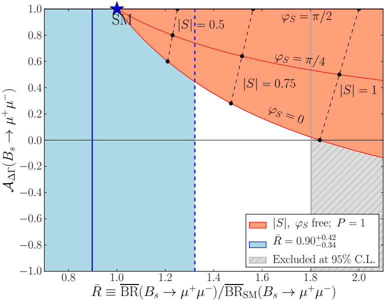
$$\Gamma(\mathbf{B_{s,L}} \to \mu^+\mu^-) \propto |\mathbf{P}|^2 \underbrace{\sin^2(\varphi_\mathbf{P} - \phi_s^{\rm NP}/2)}_{\text{scenario A}} + \underbrace{|\mathbf{S}|^2 \cos^2(\varphi_\mathbf{S} - \phi_s^{\rm NP}/2)}_{\text{scenario B}}$$

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



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

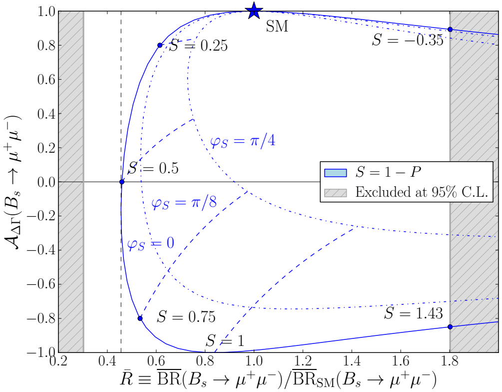
Scenario B: $\mathbf{S \neq 0}$ $(P = 1)$



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

New scalar and pseudoscalar operators on same footing

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



Realised for:

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

E.g: Decoupled 2HDM/MSSM
$(M_{H^0} \approx M_{A^0} \gg M_{h^0})$

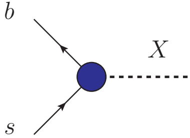
- Full range of $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ without CP violating phases
- Strict lower bound $\overline{R} \geq (1 - y_s)/2$

Compatibility with B_s mixing constraints

Consider Specific Models:

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

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



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

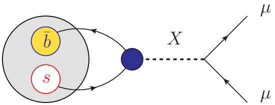
- Apply B_s mixing constraints: (see J. Girrbach's talk)

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

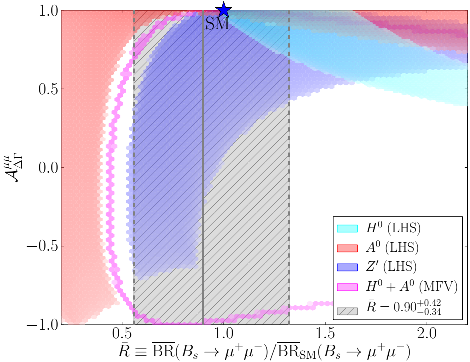
A.J. Buras, F. De Fazio, J. Girrbach, RK, M. Nagai arXiv:1303.3723

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

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



- Lepton couplings left free
- $\Delta M_{s,\text{th}} > \Delta M_{s,\text{exp}} \implies$ Z', H^0, A^0 require deviation from ϕ_s^{SM}
- $H^0 + A^0$ independent of ϕ_s



Very possible that **NP hidden** within $\overline{\mathrm{BR}}(B_s \to \mu\mu)$ bounds.
Expose with time-dependent measurement!

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

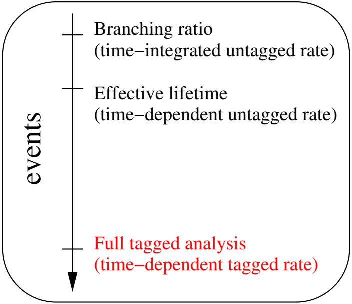
Eventually also tagged measurement:

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

- $\mathcal{S}_{\mu\mu}$ **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



Summary

$\boxed{\Gamma_{\rm L} \neq \Gamma_{\rm H}}$ implies:

- Access to mass-eigenstate rate asymmetries ($\mathcal{A}^{\rm f}_{\Delta\Gamma}$) from **time-dependent untagged** measurements

  e.g. **effective lifetimes**

- Branching ratio dictionary:

$$\mathrm{BR}(B_s \to f) \quad \overset{\mathcal{A}^{\rm f}_{\Delta\Gamma}/\tau_{\rm f}}{\longleftrightarrow} \quad \overline{\mathrm{BR}}(B_s \to f)$$

- B_s^0–$\bar{B}_s^0$ mixing constraints from effective lifetimes (τ_{f_+}, τ_{f_-})
- New topic for LHC upgrade: $\mathcal{A}^{\rm f}_{\Delta\Gamma}$ for Rare decays e.g $B_s \to \mu^+\mu^-$

Overview of references at Paperscape.org : http://pscp.me/Qg7DrE1n

Backup Slides

Helicity dependent time-dependent rates

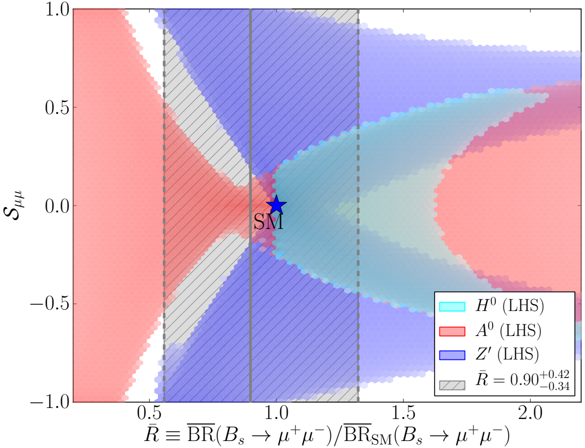
$$\Gamma(B_s^0(t) \to \mu_\lambda^+ \mu_\lambda^-) \propto \Bigg\{ \mathcal{C}_{\mu\mu}^\lambda \cos(\Delta M_s\, t) + \mathcal{S}_{\mu\mu} \cos(\Delta M_s\, t) + \cosh\left(\frac{y_s\, t}{\tau_{B_s}}\right) + \mathcal{A}_{\Delta\Gamma}^{\mu\mu} \sinh\left(\frac{y_s\, t}{\tau_{B_s}}\right) \Bigg\} \times\ e^{-t/\tau_{B_s}},$$

$$\mathcal{C}_{\mu\mu}^\lambda = -\eta_\lambda \left[\frac{2|PS|\cos(\varphi_P - \varphi_S)}{|P|^2 + |S|^2}\right],$$

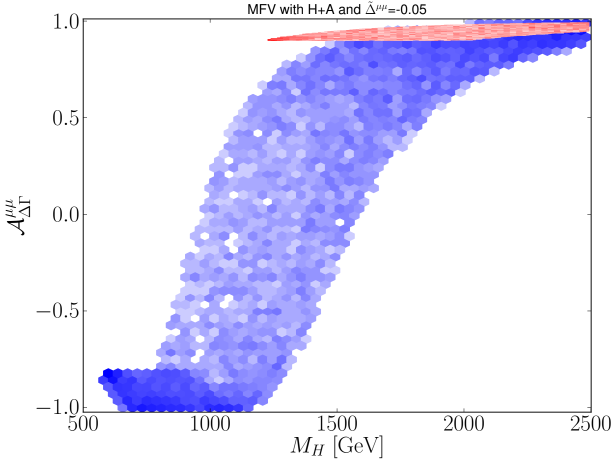
$$\mathcal{S}_{\mu\mu} = \frac{|P|^2 \sin(2\varphi_P - \phi_s^{\mathrm{NP}}) - |S|^2 \sin(2\varphi_S - \phi_s^{\mathrm{NP}})}{|P|^2 + |S|^2},$$

$$\mathcal{A}_{\Delta\Gamma}^{\mu\mu} = \frac{|P|^2 \cos(2\varphi_P - \phi_s^{\mathrm{NP}}) - |S|^2 \cos(2\varphi_S - \phi_s^{\mathrm{NP}})}{|P|^2 + |S|^2}.$$

Parameter space with $B_s \to \mu^+\mu^-$ tagged analysis



Mass dependence of $\mathcal{A}^f_{\Delta\Gamma}$ in $H^0 + A^0$ model



Fitting an effective lifetime

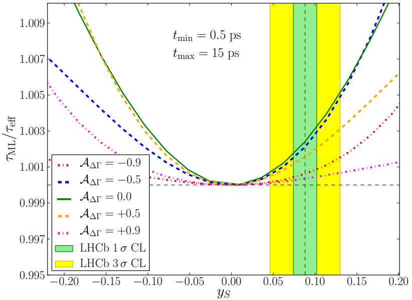
$$f_{\rm true}(t) \equiv \frac{A(t)\,\langle\Gamma(t)\rangle}{\int_0^\infty A(t)\,\langle\Gamma(t)\rangle\,dt}, \qquad f_{\rm fit}(t;\tau) \equiv \frac{A(t)\,e^{-t/\tau}}{\int_0^\infty A(t)\,e^{-t/\tau}\,dt}$$

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:

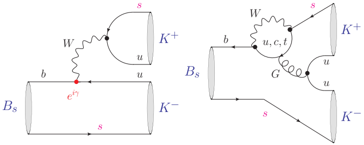
$$\frac{\Gamma\left(B_s(t) \to f\right) - \Gamma(\bar{B}_s(t) \to f)}{\Gamma(B_s(t) \to f) + \Gamma(\bar{B}_s(t) \to f)} = \frac{C \cos(\Delta M_s\, t) - S \sin(\Delta M_s\, t)}{\cosh(\Delta\Gamma_s\, t) + \mathcal{A}_{\Delta\Gamma} \sinh(\Delta\Gamma_s\, t)}$$

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

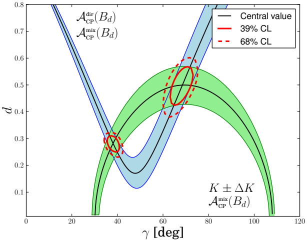
$$\lambda_f \equiv \frac{q}{p}\; \frac{A(\overline{B}_s^0 \to f)}{A(B_s^0 \to f)} = -\eta\; e^{-i\phi_s}\; \sqrt{\frac{1-C}{1+C}}\, e^{-i\Delta\phi}$$

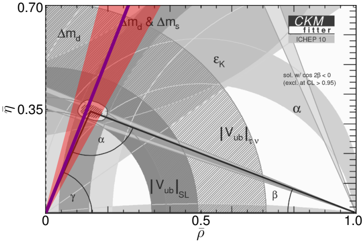
$$\mathcal{A}_{\Delta\Gamma} - i\, S = \frac{2\;\lambda_f}{1+|\lambda_f|^2} = \boxed{-\eta\,\sqrt{1-C^2}\; e^{-i(\phi_s+\Delta\phi)}}$$

U-spin control ob $B_s \to K^+K^-$



$$A(B_s^0 \to K^+K^-) = \lambda\,\mathcal{C}\left[e^{i\gamma} + \frac{1}{\epsilon} d\, e^{i\theta}\right]$$





$$\gamma = (68 \pm 7)^\circ, \quad d = 0.50^{+0.12}_{-0.11}, \quad \theta = \left(154^{+11}_{-14}\right)^\circ$$

R. Fleischer, Phys.Lett.B 459 (1999) 306, *R. Fleischer and RK, Eur.Phys.J. C71 (2011) 1532*