New Perspectives to Probe New Physics with $B_s^0 \to \mu^+\mu^-$

ROBERT FLEISCHER

Nikhef & Vrije Universiteit Amsterdam

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- Setting the Stage

- Recent Development: $\Delta\Gamma_s \neq 0 \to$ affects BR(B_s) in a subtle way ...

- Impact on $B_s \to \mu^+\mu^-$ (?): $\Rightarrow$ BR $+$ new window for New Physics:

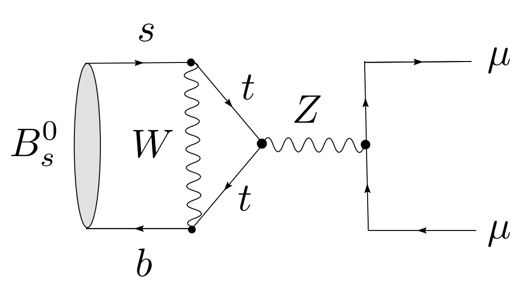
  $\to$ illustration in specific NP scenarios

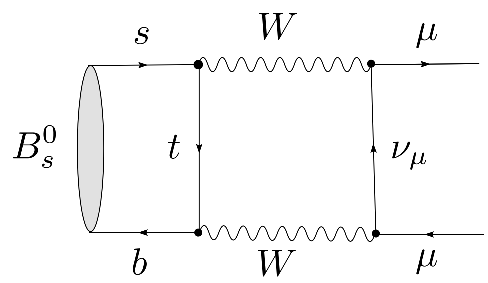
- Conclusions

Setting the Stage

General Features of $B_s^0 \to \mu^+\mu^-$

- Situation in the Standard Model (SM): $\to$ only loop contributions:





  – Moreover: helicity suppression $\to$ BR $\propto m_\mu^2$

$\Rightarrow$ **strongly suppressed decay**

- Hadronic sector: $\to$ very simple, only the B_s decay constant F_{B_s} enters:

$$\langle 0|\bar{b}\gamma_5\gamma_\mu s|B_s^0(p)\rangle = iF_{B_s}p_\mu$$

$\Rightarrow$ **$B_s^0 \to \mu^+\mu^-$ belongs to the cleanest rare B decays**

SM Prediction of the $B_s \to \mu^+\mu^-$ Branching Ratio

- Parametric dependence on the relevant input parameters:

  [Refers to the "theoretical" branching ratio, see discussion below]

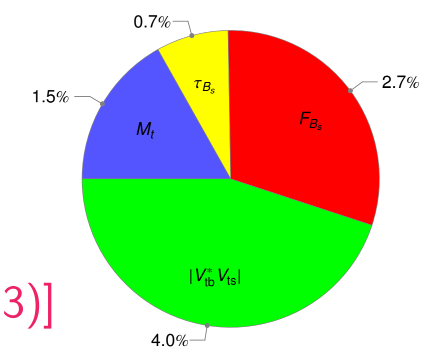
$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = 3.25 \times 10^{-9} \times \left[\frac{M_t}{173.2\,\mathrm{GeV}}\right]^{3.07} \left[\frac{F_{B_s}}{225\,\mathrm{MeV}}\right]^2 \left[\frac{\tau_{B_s}}{1.500\mathrm{ps}}\right] \left|\frac{V_{tb}^* V_{ts}}{0.0405}\right|^2$$

[Buras, Girrbach, Guadagnoli & Isidori (2012); address also soft photon corrections]

- Most relevant recent changes:
  - Lattice QCD progress [FLAG]: $F_{B_s} = (227.7 \pm 4.5)$ MeV
  - Experiment [HFAG]: $\tau_{B_s} = (1.516 \pm 0.011)$ ps
  - Theory: [Bobeth *et al.*, arXiv:1311.0903]

    NLO electroweak effects [Bobeth *et al.*, arXiv:1311.1348] and NNLO QCD matching corrections [Herman *et al.*, arXiv:1311.1347]:

$$\Rightarrow \boxed{\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.38 \pm 0.22) \times 10^{-9}}$$

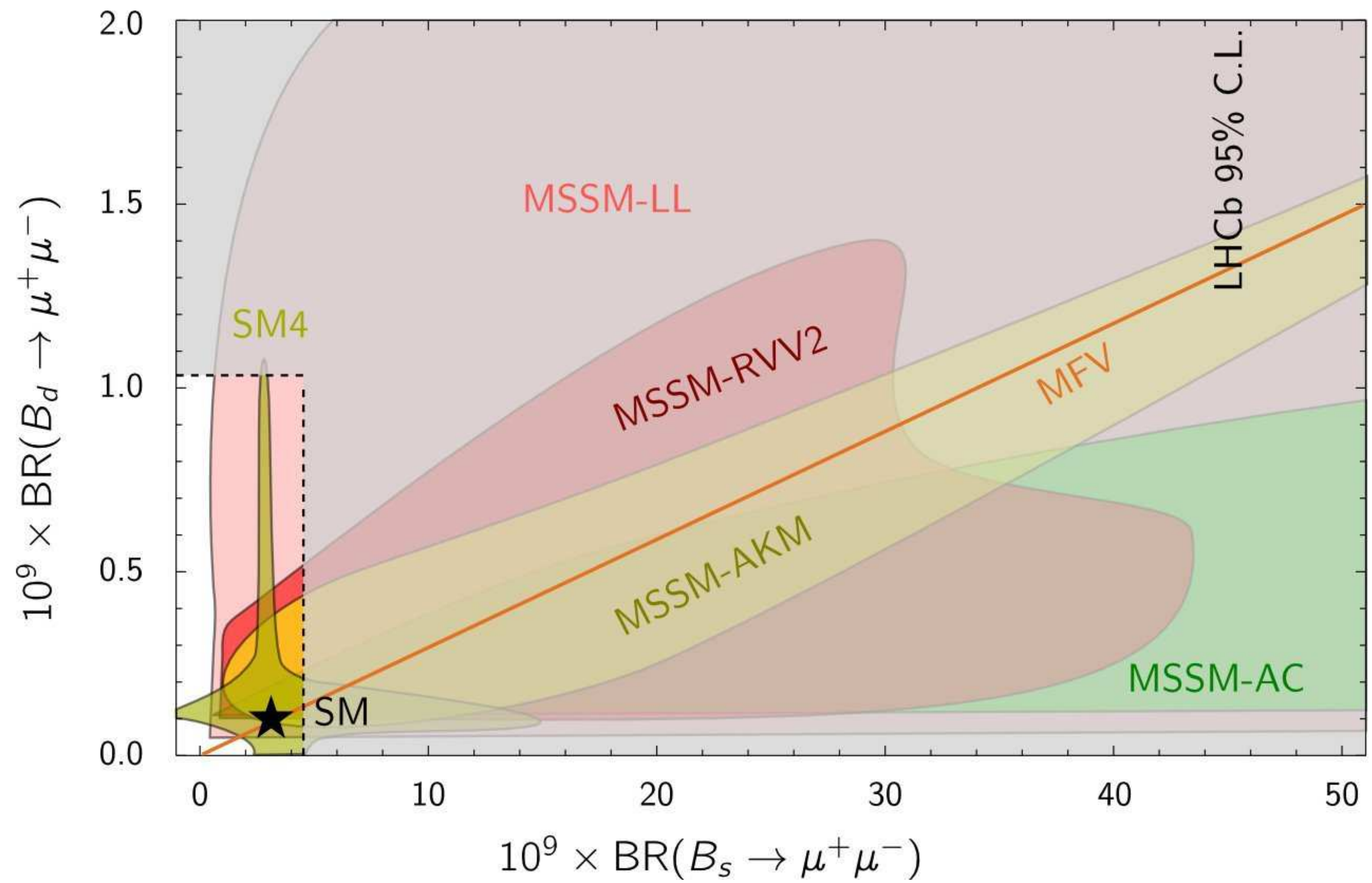


[supersedes prediction by Buras, R.F., Girrbach & Knegjens (2013)]

Impact of NP on the $B_{s(d)} \to \mu^+\mu^-$ Branching Ratios

- May (in principle ...) enhance the branching ratios significantly:

  $\to$ illustration in different supersymmetric flavour models:



[D. Straub (2010); A.J. Buras & J. Girrbach (2012)]

Current Experimental Status of $B_s \to \mu^+\mu^-$

- Tevatron: $\to$ *"legacy"* ...
  - DØ (2013): BR$(B_s \to \mu^+\mu^-) < 15 \times 10^{-9}$ (95% C.L.)
  - CDF (2013): BR$(B_s \to \mu^+\mu^-) < 31 \times 10^{-9}$ (95% C.L.)

- Large Hardon Collider: $\to$ *future* ... [$\to$ talk by Patrick Spradlin]
  - ATLAS (2013): BR$(B_s \to \mu^+\mu^-) < 15 \times 10^{-9}$ (95% C.L.)

  ... and finally *evidence* for $B_s \to \mu^+\mu^-$ @ CMS and LHCb:

  - CMS (2013): BR$(B_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$
  - LHCb (2013): BR$(B_s \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$

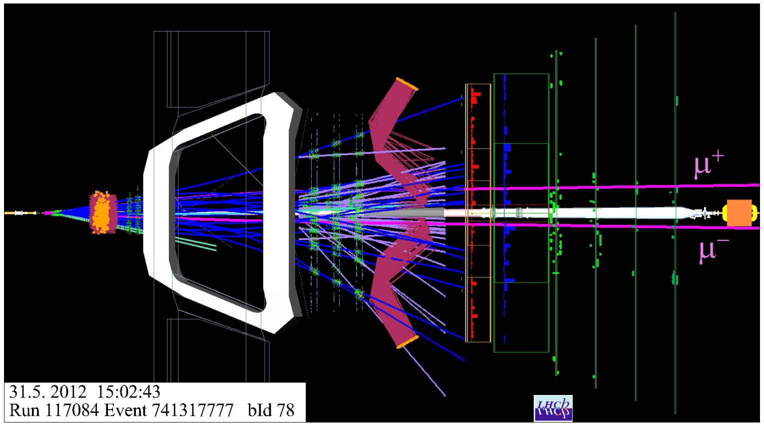
  $\Rightarrow$ average: $\boxed{\text{BR}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}}$

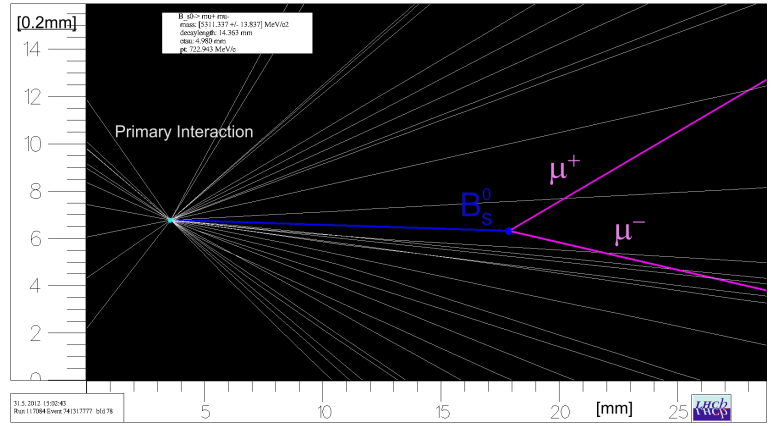
  [CMS-PAS-BPH-13-007, LHCb-CONF-2013-012]

- Note: *the* limiting factor for the BR$(B_s \to \mu^+\mu^-)$ measurement – and all B_s branching ratios – is the ratio of f_s/f_d fragmentation functions.

  [Details: R.F., Serra & Tuning (2010); Fermilab Lattice & MILC Collaborations (2012)]

- Candidate $B_s \to \mu^+\mu^-$ signal event @ LHCb:





- It will be interesting to keep an eye on $B_d \to \mu^+\mu^-$:

  – $\text{BR}(B_d \to \mu^+\mu^-)|_{\text{CMS}} = (3.5^{+2.1}_{-1.8}) \times 10^{-10} \quad < 11 \times 10^{-10}$ (95% C.L.)

  – $\text{BR}(B_d \to \mu^+\mu^-)|_{\text{LHCb}} = (3.7^{+2.4}_{-2.1}) \times 10^{-10} < 7.4 \times 10^{-10}$ (95% C.L.)

  $\Rightarrow$ average: $\boxed{\text{BR}(B_d \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10}}$

  [CMS-PAS-BPH-13-007, LHCb-CONF-2013-012]

  – Standard Model prediction [Bobeth *et al.*, arXiv:1311.0903]:

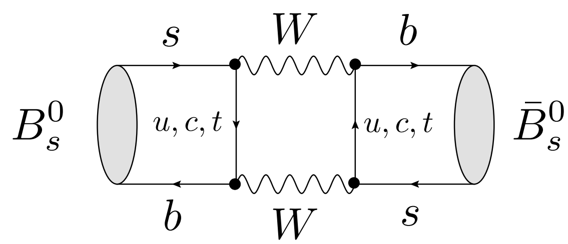
  $\boxed{\text{BR}(B_d \to \mu^+\mu^-)_{\text{SM}} = (1.06 \pm 0.09) \times 10^{-10}} \Rightarrow$!? ...

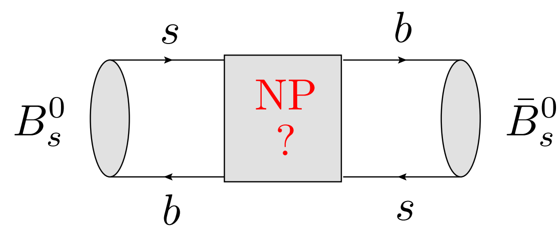
Recent Development:

$$\Delta\Gamma_s \neq 0$$

◇ *Seemingly* unrelated topic, *but* ...

B_s^0–$\bar{B}_s^0$ Mixing & Decay Width Difference $\Delta\Gamma_s$





- Quantum mechanics: $\Rightarrow \quad |B_s(t)\rangle = a(t)|B_s^0\rangle + b(t)|\bar{B}_s^0\rangle$
  - Mass eigenstates: $\Delta M_s \equiv M_{\rm H}^{(s)} - M_{\rm L}^{(s)}, \quad \Delta\Gamma_s \equiv \Gamma_{\rm L}^{(s)} - \Gamma_{\rm H}^{(s)}$
  - Time-dependent decay rates: $\Gamma(B_s^0(t) \to f), \quad \Gamma(\bar{B}_s^0(t) \to f)$

- Key feature of the B_s-meson system: $\boxed{\Delta\Gamma_s \neq 0}$
  - Expected theoretically since decades [Recent review: A. Lenz (2012)].
  - Now established at the $6\,\sigma$ level [LHCb: arXiv:1304.2600]:

$$y_s \equiv \frac{\Delta\Gamma_s}{2\,\Gamma_s} \equiv \frac{\Gamma_{\rm L}^{(s)} - \Gamma_{\rm H}^{(s)}}{2\,\Gamma_s} = 0.075 \pm 0.012$$

$\rightarrow B_s$ Branching Ratios:

- $\Delta\Gamma_s \neq 0 \Rightarrow$ *special care* has to be taken when dealing with the concept of a branching ratio ...

- How to *convert* measured "experimental" B_s branching ratios into "theoretical" B_s branching ratios?

[De Bruyn, R.F., Knegjens, Koppenburg, Merk and Tuning
Phys. Rev. **D 86** (2012) 014027 [arXiv:1204.1735 [hep-ph]]]

Experiment vs. Theory

- Untagged B_s decay rate: $\rightarrow$ *sum of two exponentials:*

$$\langle\Gamma(B_s(t)\to f)\rangle \equiv \Gamma(B^0_s(t)\to f)+\Gamma(\bar{B}^0_s(t)\to f) = R^f_{\rm H}e^{-\Gamma^{(s)}_{\rm H}t}+R^f_{\rm L}e^{-\Gamma^{(s)}_{\rm L}t}$$

$$= \left(R^f_{\rm H}+R^f_{\rm L}\right)e^{-\Gamma_s t}\left[\cosh\left(\frac{y_s\,t}{\tau_{B_s}}\right)+\mathcal{A}^f_{\Delta\Gamma}\sinh\left(\frac{y_s\,t}{\tau_{B_s}}\right)\right]$$

- "Experimental" branching ratio: [I. Dunietz, R.F. & U. Nierste (2001)]

$$\mathrm{BR}\,(B_s\to f)_{\rm exp} \equiv \overline{\mathrm{BR}}\,(B_s\to f) \equiv \frac{1}{2}\int_0^\infty \langle\Gamma(B_s(t)\to f)\rangle\,dt$$

$$= \frac{1}{2}\left[\frac{R^f_{\rm H}}{\Gamma^{(s)}_{\rm H}}+\frac{R^f_{\rm L}}{\Gamma^{(s)}_{\rm L}}\right] = \frac{\tau_{B_s}}{2}\left(R^f_{\rm H}+R^f_{\rm L}\right)\left[\frac{1+\mathcal{A}^f_{\Delta\Gamma}\,y_s}{1-y_s^2}\right] \qquad (6)$$

- "Theoretical" branching ratio: [R.F. (1999); S. Faller, R.F. & T. Mannel (2008); ...]

$$\mathrm{BR}\,(B_s\to f) \equiv \frac{\tau_{B_s}}{2}\langle\Gamma(B^0_s(t)\to f)\rangle\Big|_{t=0} = \frac{\tau_{B_s}}{2}\left(R^f_{\rm H}+R^f_{\rm L}\right) \qquad (8)$$

  – By considering $t=0$, the effect of B^0_s–$\bar{B}^0_s$ mixing is "switched off".

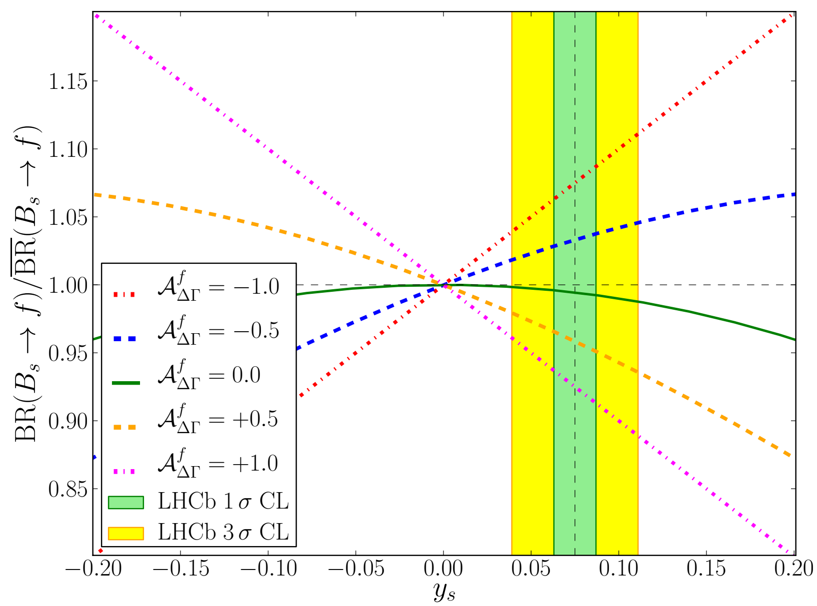
  – The advantage of this definition is that it allows a straightforward comparison with the BRs of B^0_d or B^+_u mesons by means of $SU(3)_{\rm F}$.

Conversion of B_s Decay Branching Ratios

- Relation between $\mathrm{BR}\,(B_s \to f)$ and the measured $\overline{\mathrm{BR}}\,(B_s \to f)$:

$$\mathrm{BR}\,(B_s \to f) = \left[\frac{1 - y_s^2}{1 + \mathcal{A}_{\Delta\Gamma}^f\, y_s}\right] \overline{\mathrm{BR}}\,(B_s \to f) \tag{9}$$

- While $y_s = 0.075 \pm 0.012$ has been measured, $\mathcal{A}_{\Delta\Gamma}^f$ depends on the considered decay and generally involves non-perturbative parameters:



$\Rightarrow$ differences as large as $\mathcal{O}(10\%)$ for the measured value of y_s

- Compilation of theoretical estimates for specific B_s decays:

$B_s \to f$	$\mathrm{BR}(B_s \to f)_{\mathrm{exp}}$	$\mathcal{A}^f_{\Delta\Gamma}(\mathrm{SM})$	$\mathrm{BR}\,(B_s \to f)_{\mathrm{theo}}/\mathrm{BR}\,(B_s \to f)_{\mathrm{exp}}$ From Eq. (9)	From Eq. (11)
$J/\psi f_0(980)$	$(1.29^{+0.40}_{-0.28}) \times 10^{-4}$ [18]	0.9984 ± 0.0021 [14]	0.912 ± 0.014	0.890 ± 0.082 [6]
$J/\psi K_{\mathrm{S}}$	$(3.5 \pm 0.8) \times 10^{-5}$ [7]	0.84 ± 0.17 [15]	0.924 ± 0.018	N/A
$D_s^- \pi^+$	$(3.01 \pm 0.34) \times 10^{-3}$ [9]	0 (exact)	0.992 ± 0.003	N/A
K^+K^-	$(3.5 \pm 0.7) \times 10^{-5}$ [18]	-0.972 ± 0.012 [13]	1.085 ± 0.014	1.042 ± 0.033 [19]
$D_s^+ D_s^-$	$(1.04^{+0.29}_{-0.26}) \times 10^{-2}$ [18]	-0.995 ± 0.013 [16]	1.088 ± 0.014	N/A

TABLE I: Factors for converting $\mathrm{BR}\,(B_s \to f)_{\mathrm{exp}}$ (see (6)) into $\mathrm{BR}\,(B_s \to f)_{\mathrm{theo}}$ (see (8)) by means of Eq. (9) with theoretical estimates for $\mathcal{A}^f_{\Delta\Gamma}$. Whenever effective lifetime information is available, the corrections are also calculated using Eq. (11).

How can we avoid theoretical input? $\to$

- Effective B_s decay lifetimes:

$$\tau_f \equiv \frac{\int_0^\infty t\,\langle\Gamma(B_s(t) \to f)\rangle\,dt}{\int_0^\infty \langle\Gamma(B_s(t) \to f)\rangle\,dt} = \frac{\tau_{B_s}}{1-y_s^2}\left[\frac{1 + 2\,\mathcal{A}^f_{\Delta\Gamma} y_s + y_s^2}{1 + \mathcal{A}^f_{\Delta\Gamma} y_s}\right]$$

$$\Rightarrow \boxed{\mathrm{BR}\,(B_s \to f) = \left[2 - \left(1 - y_s^2\right)\tau_f/\tau_{B_s}\right]\overline{\mathrm{BR}}\,(B_s \to f)} \qquad (11)$$

$\to$ *advocate the use of this relation for Particle Listings (PDG, HFAG)*

Key B_s Decay: $B_s \to \mu^+\mu^-$

- Experimental BR falls into the SM regime ...
- What is the impact of $\Delta\Gamma_s \neq 0$ on these analyses?

$\to$ *Opens actually a new window for New Physics*

[De Bruyn, R.F., Knegjens, Koppenburg, Merk, Pellegrino and Tuning
Phys. Rev. Lett. **109** (2012) 041801 [arXiv:1204.1737 [hep-ph]]]

The General $B_s \to \mu^+\mu^-$ Amplitudes

- Low-energy effective Hamiltonian for $\bar{B}^0_s \to \mu^+\mu^-$: SM $\oplus$ NP

$$\mathcal{H}_{\rm eff} = -\frac{G_{\rm F}}{\sqrt{2}\pi} V^*_{ts} V_{tb} \alpha \left[C_{10} O_{10} + C_S O_S + C_P O_P + C'_{10} O'_{10} + C'_S O'_S + C'_P O'_P \right]$$

[$G_{\rm F}$: Fermi's constant, $V_{qq'}$: CKM matrix elements, α: QED fine structure constant]

- Four-fermion operators, with $P_{L,R} \equiv (1 \mp \gamma_5)/2$ and b-quark mass m_b:

$$\begin{aligned} O_{10} &= (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell), & O'_{10} &= (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5\ell) \\ O_S &= m_b(\bar{s}P_R b)(\bar{\ell}\ell), & O'_S &= m_b(\bar{s}P_L b)(\bar{\ell}\ell) \\ O_P &= m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell), & O'_P &= m_b(\bar{s}P_L b)(\bar{\ell}\gamma_5\ell) \end{aligned}$$

[Only operators with non-vanishing $\bar{B}^0_s \to \mu^+\mu^-$ matrix elements are included]

- The Wilson coefficients C_i, C'_i encode the short-distance physics:
  - SM case: only $C_{10} \neq 0$, and is given by the *real* coefficient $C_{10}^{\rm SM}$.
  - *Outstanding feature of* $\bar{B}^0_s \to \mu^+\mu^-$: sensitivity to (pseudo-)scalar lepton densities $\to O_{(P)S}$, $O'_{(P)S}$; WCs are still largely unconstrained.

[Altmannshofer, Paradisi & Straub (2011); ... $\to$ model-independent NP analyses]

$\rightarrow$ *convenient to go to the rest frame of the decaying $\bar{B}^0_s$ meson:*

- Distinguish between the $\mu^+_{\rm L}\mu^-_{\rm L}$ and $\mu^+_{\rm R}\mu^-_{\rm R}$ helicity configurations:

$$|(\mu^+_{\rm L}\mu^-_{\rm L})_{\rm CP}\rangle \equiv (\mathcal{CP})|\mu^+_{\rm L}\mu^-_{\rm L}\rangle = e^{i\phi_{\rm CP}(\mu\mu)}|\mu^+_{\rm R}\mu^-_{\rm R}\rangle$$

[$e^{i\phi_{\rm CP}(\mu\mu)}$ is a convention-dependent phase factor $\rightarrow$ cancels in observables]

- General expression for the decay amplitude [$\eta_{\rm L}=+1$, $\eta_{\rm R}=-1$]:

$$A(\bar{B}^0_s \to \mu^+_\lambda\mu^-_\lambda) = \langle\mu^-_\lambda\mu^+_\lambda|\mathcal{H}_{\rm eff}|\bar{B}^0_s\rangle = -\frac{G_{\rm F}}{\sqrt{2}\pi}V^*_{ts}V_{tb}\alpha$$

$$\times F_{B_s}M_{B_s}m_\mu C_{10}^{\rm SM}e^{i\phi_{\rm CP}(\mu\mu)(1-\eta_\lambda)/2}\left[\eta_\lambda P + S\right]$$

- Combination of Wilson coefficient functions [CP-violating phases $\varphi_{P,S}$]:

$$P \equiv |P|e^{i\varphi_P} \equiv \frac{C_{10}-C_{10}'}{C_{10}^{\rm SM}} + \frac{M_{B_s}^2}{2\,m_\mu}\left(\frac{m_b}{m_b+m_s}\right)\left(\frac{C_P-C_P'}{C_{10}^{\rm SM}}\right) \xrightarrow{\rm SM} 1$$

$$S \equiv |S|e^{i\varphi_S} \equiv \sqrt{1-4\frac{m_\mu^2}{M_{B_s}^2}}\frac{M_{B_s}^2}{2\,m_\mu}\left(\frac{m_b}{m_b+m_s}\right)\left(\frac{C_S-C_S'}{C_{10}^{\rm SM}}\right) \xrightarrow{\rm SM} 0$$

[F_{B_s}: B_s decay constant, M_{B_s}: B_s mass, m_μ: muon mass, m_s: strange-quark mass]

The $B_s \to \mu^+\mu^-$ Observables

- Key quantity for calculating the CP asymmetries and the untagged rate:

$$\xi_\lambda \equiv -e^{-i\phi_s}\left[e^{i\phi_{\rm CP}(B_s)}\frac{A(\bar{B}^0_s \to \mu^+_\lambda\mu^-_\lambda)}{A(B^0_s \to \mu^+_\lambda\mu^-_\lambda)}\right]$$

$$\Rightarrow A(B^0_s \to \mu^+_\lambda\mu^-_\lambda) = \langle \mu^-_\lambda\mu^+_\lambda|\mathcal{H}^\dagger_{\rm eff}|B^0_s\rangle \text{ is also needed ...}$$

- Using $(\mathcal{CP})^\dagger(\mathcal{CP}) = \hat{1}$ and $(\mathcal{CP})|B^0_s\rangle = e^{i\phi_{\rm CP}(B_s)}|\bar{B}^0_s\rangle$ yields:

$$A(B^0_s \to \mu^+_\lambda\mu^-_\lambda) = -\frac{G_{\rm F}}{\sqrt{2}\pi}V_{ts}V^*_{tb}\alpha f_{B_s}M_{B_s}m_\mu C_{10}^{\rm SM}$$

$$\times\, e^{i[\phi_{\rm CP}(B_s)+\phi_{\rm CP}(\mu\mu)(1-\eta_\lambda)/2]}\left[-\eta_\lambda P^* + S^*\right]$$

- The convention-dependent phases cancel in ξ_λ $[\eta_{\rm L} = +1,\ \eta_{\rm R} = -1]$:

$$\xi_\lambda = -\left[\frac{+\eta_\lambda P + S}{-\eta_\lambda P^* + S^*}\right] \quad \Rightarrow \quad \boxed{\xi_{\rm L}\xi^*_{\rm R} = \xi_{\rm R}\xi^*_{\rm L} = 1}$$

CP Asymmetries:

- Time-dependent rate asymmetry: $\rightarrow$ *requires tagging of B_s^0 and $\bar{B}_s^0$:*

$$\frac{\Gamma(B_s^0(t)\to\mu_\lambda^+\mu_\lambda^-)-\Gamma(\bar{B}_s^0(t)\to\mu_\lambda^+\mu_\lambda^-)}{\Gamma(B_s^0(t)\to\mu_\lambda^+\mu_\lambda^-)+\Gamma(\bar{B}_s^0(t)\to\mu_\lambda^+\mu_\lambda^-)}=\frac{C_\lambda\cos(\Delta M_s t)+S_\lambda\sin(\Delta M_s t)}{\cosh(y_s t/\tau_{B_s})+\mathcal{A}_{\Delta\Gamma}^\lambda\sinh(y_s t/\tau_{B_s})}$$

- Observables: $\rightarrow$ *theoretically clean (no dependence on F_{B_s}):*

$$C_\lambda\equiv\frac{1-|\xi_\lambda|^2}{1+|\xi_\lambda|^2}=-\eta_\lambda\left[\frac{2|PS|\cos(\varphi_P-\varphi_S)}{|P|^2+|S|^2}\right]\quad\xrightarrow{\text{SM}}\quad 0$$

$$S_\lambda\equiv\frac{2\,\mathrm{Im}\,\xi_\lambda}{1+|\xi_\lambda|^2}=\frac{|P|^2\sin(2\varphi_P-\phi_s^{\rm NP})-|S|^2\sin(2\varphi_S-\phi_s^{\rm NP})}{|P|^2+|S|^2}\quad\xrightarrow{\text{SM}}\quad 0$$

$$\mathcal{A}_{\Delta\Gamma}^\lambda\equiv\frac{2\,\mathrm{Re}\,\xi_\lambda}{1+|\xi_\lambda|^2}=\frac{|P|^2\cos(2\varphi_P-\phi_s^{\rm NP})-|S|^2\cos(2\varphi_S-\phi_s^{\rm NP})}{|P|^2+|S|^2}\quad\xrightarrow{\text{SM}}\quad 1$$

[$\phi_s^{\rm NP}$ is the NP component of the B_s^0–$\bar{B}_s^0$ mixing phase $\phi_s=-2\lambda^2\eta+\phi_s^{\rm NP}$]

- Note: $\mathcal{S}_{\mu\mu}\equiv S_\lambda$, $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}\equiv\mathcal{A}_{\Delta\Gamma}^\lambda$ are *independent* of the muon helicity λ.

- Difficult to measure the muon helicity: $\Rightarrow$ *consider the following rates:*

$$\Gamma(\overset{(-)}{B}{}^0_s(t) \to \mu^+\mu^-) \equiv \sum_{\lambda=\mathrm{L,R}} \Gamma(\overset{(-)}{B}{}^0_s(t) \to \mu^+_\lambda \mu^-_\lambda)$$

- Corresponding CP-violating rate asymmetry: $\to$ $C_\lambda \propto \eta_\lambda$ *terms cancel:*

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

- Practical comments:
  - It would be most interesting to measure this CP asymmetry as a non-zero value would signal CP-violating NP phases [$\to$ see below].
  - Unfortunately, this is challenging in view of the tiny branching ratio and as B^0_s, $\bar{B}^0_s$ *tagging* and time information are required.

[Previous studies of CP asymmetries of $B^0_{s,d} \to \ell^+\ell^-$ (assuming $\Delta\Gamma_s = 0$):
Huang and Liao (2002); Dedes and Pilaftsis (2002), Chankowski *et al.* (2005)]

Untagged Rate and Branching Ratio:

- The first measurement concerns the "experimental" branching ratio:

$$\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) \equiv \frac{1}{2}\int_0^\infty \langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle \, dt$$

$\to$ *time-integrated untagged rate,* involving

$$\langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle \equiv \Gamma(B_s^0(t) \to \mu^+\mu^-) + \Gamma(\bar{B}_s^0(t) \to \mu^+\mu^-)$$

$$\propto e^{-t/\tau_{B_s}}\left[\cosh(y_s t/\tau_{B_s}) + \mathcal{A}_{\Delta\Gamma}^{\mu\mu}\sinh(y_s t/\tau_{B_s})\right]$$

- Conversion into the "theoretical" branching ratio (referring to $t=0$):

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

- The observable $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ depends on NP and is hence unknown:

$$\mathcal{A}_{\Delta\Gamma}^{\mu\mu} \in [-1,+1] \quad \Rightarrow \quad \textit{two options:}$$

(i) Add an extra error to the experimental branching ratio:

$$\Delta \mathrm{BR}(B_s \to \mu^+\mu^-)|_{y_s} = \pm y_s \overline{\mathrm{BR}}(B_s \to \mu^+\mu^-).$$

(ii) $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}|_{\mathrm{SM}} = +1$ gives a *new SM reference value* for the comparison with the time-integrated experimental branching ratio $\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)$:

$\Rightarrow$ rescale $\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}$ by $1/(1-y_s)$:

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

[Bobeth *et al.* (2013), supersedes Buras, R.F., Girrbach & Knegjens (2013)]

Effective $B_s \to \mu^+\mu^-$ Lifetime:

◇ *Collecting more and more data* $\oplus$ *include decay time information* $\Rightarrow$

- Access to the effective $B_s \to \mu^+\mu^-$ lifetime:

$$\tau_{\mu\mu} \equiv \frac{\int_0^\infty t\,\langle\Gamma(B_s(t)\to\mu^+\mu^-)\rangle\,dt}{\int_0^\infty \langle\Gamma(B_s(t)\to\mu^+\mu^-)\rangle\,dt}$$

- $\mathcal{A}^{\mu\mu}_{\Delta\Gamma}$ can then be extracted: $\mathcal{A}^{\mu\mu}_{\Delta\Gamma} = \frac{1}{y_s}\left[\frac{(1-y_s^2)\tau_{\mu\mu}-(1+y_s^2)\tau_{B_s}}{2\tau_{B_s}-(1-y_s^2)\tau_{\mu\mu}}\right]$

- Finally, extraction of the "theoretical" BR: $\to$ *clean expression:*

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

  – Note: it is *crucial* that $\mathcal{A}^{\mu\mu}_{\Delta\Gamma}$ does *not* depend on the muon helicity.

$\Rightarrow$ Interesting new measurement for the high-luminosity LHC upgrade!

Probing New Physics:

$\rightarrow \left\{ \begin{array}{l} \mathcal{A}_{\Delta\Gamma}^{\mu\mu} \text{ and } \mathcal{S}_{\mu\mu} \text{ exhibit NP sensitivity} \\ \text{that is complementary to the BR} \end{array} \right.$

- "Disclaimer":
  - Assume that the B_s^0–$\bar{B}_s^0$ mixing phase ϕ_s will be precisely known by the time the $B_s \to \mu^+\mu^-$ measurements can be made $\Rightarrow$ fixes $\phi_s^{\rm NP}$.
  - LHCb average for CP violation in $B_s^0 \to J/\psi\phi, J/\psi f_0(980)$:

    $\phi_s = [0.57 \pm 4.01(\text{stat}) \pm 0.57(\text{syst})]^\circ$ [Review: W. Hulsbergen (2013)]

[Detailed analysis: A.J. Buras, R.F., J. Girrbach & R. Knegjens ('13)
thanks to R. Knegjens for updating numerics/plots]

Branching Ratio Information

- Useful to introduce the following ratio:

$$\overline{R} \equiv \frac{\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)}{\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} = \left[\frac{1 + \mathcal{A}_{\Delta\Gamma}^{\mu\mu}\, y_s}{1 + y_s}\right] (|P|^2 + |S|^2)$$

$$= \left[\frac{1 + y_s \cos(2\varphi_P - \phi_s^{\mathrm{NP}})}{1 + y_s}\right] |P|^2 + \left[\frac{1 - y_s \cos(2\varphi_S - \phi_s^{\mathrm{NP}})}{1 + y_s}\right] |S|^2$$

  - Current situation: $\overline{R} = 0.79 \pm 0.20$
  - $\overline{R}$ does not allow a separation of the P and S contributions:

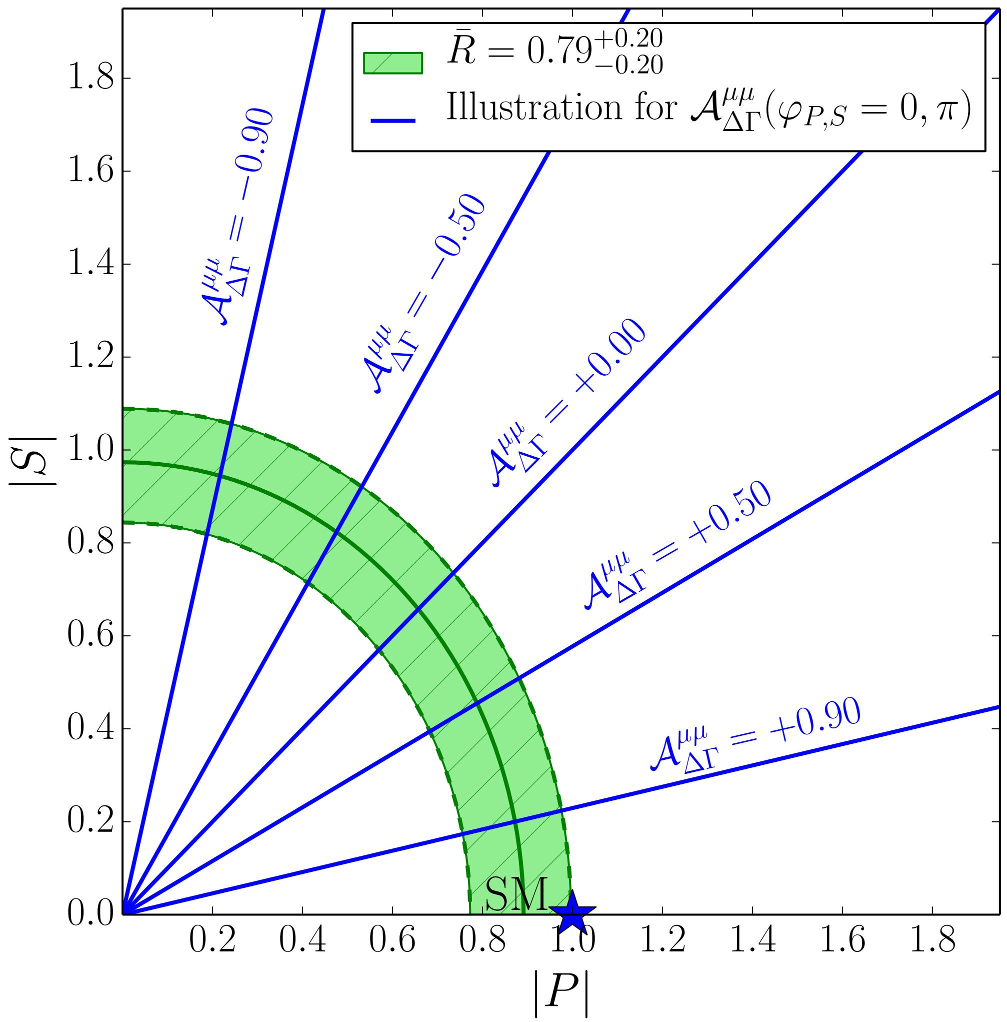
$\Rightarrow$ large NP could be present, even if $\overline{R}$ is close to $\overline{R}_{\mathrm{SM}} = 1$.

- Further information from the measurement of $\tau_{\mu\mu}$ yielding $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$:

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

$\Rightarrow$ offers a new window for NP in $B_s \to \mu^+\mu^-$

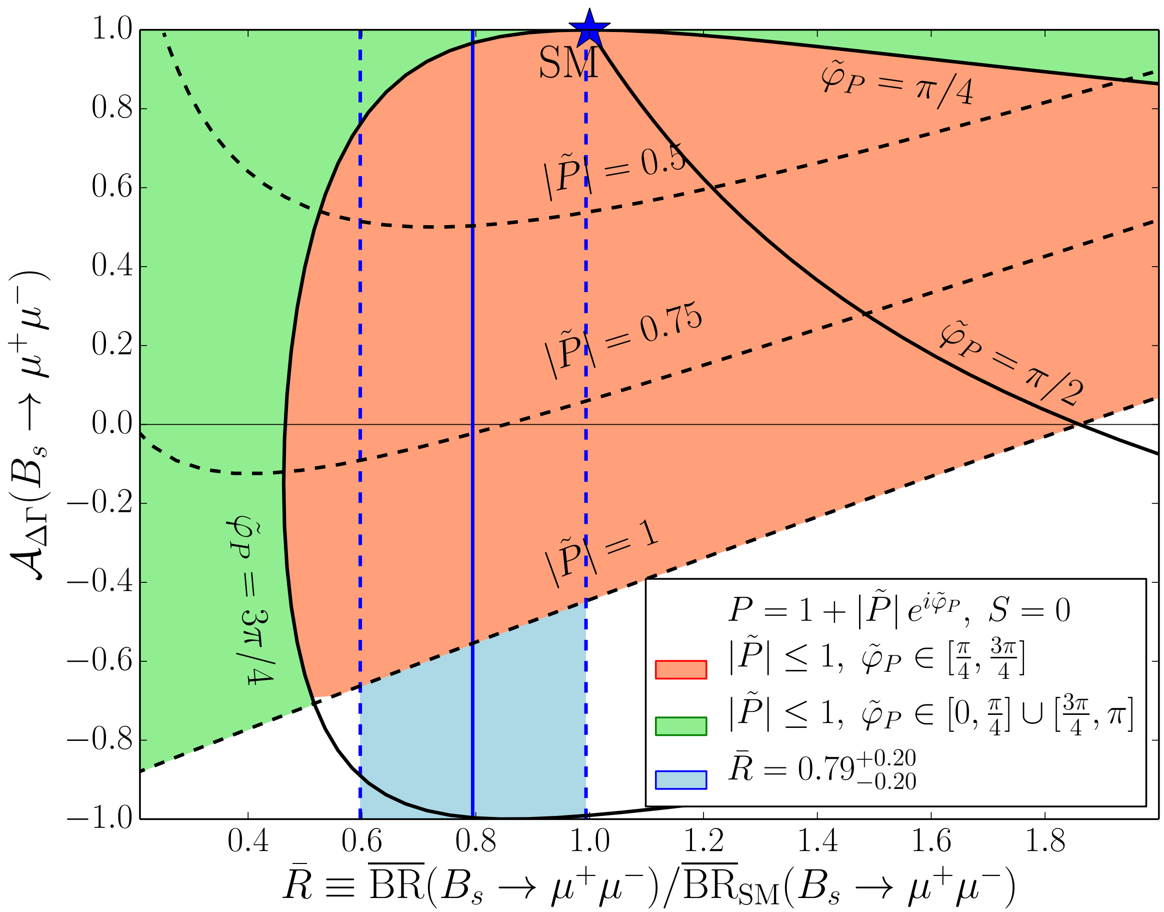
- Current constraints in the $|P|$–$|S|$ plane and illustration of those following from a future measurement of the $B_s \to \mu^+\mu^-$ lifetime yielding $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$:



[Assumes no NP phases for the $\mathcal{A}_{\Delta\Gamma}$ curves (e.g. MFV without flavour-blind phases)]

Scenario with $P = 1 + \tilde{P}$ ($\tilde{P}$ Free) and $S = 0$

$\Rightarrow$ *no new scalar operators:*

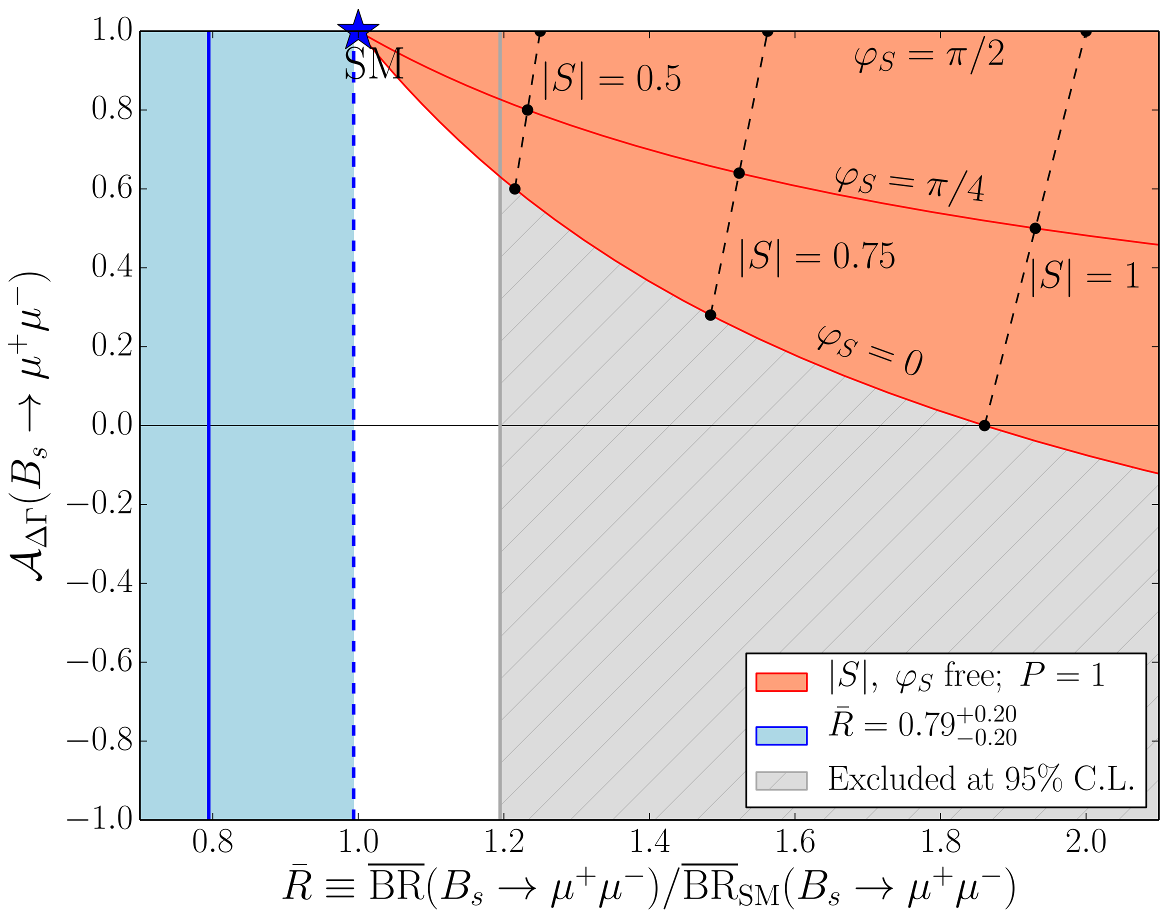


- Deviation of $\mathcal{A}^{\mu\mu}_{\Delta\Gamma}$ from SM value $+1$ requires CP-violating NP phases.

[Examples of specific models: CMFV, LHT, 4G, RSc, Z']

Scenario with $P = 1$ and S Free:

$\Rightarrow$ *only new scalar operators:*

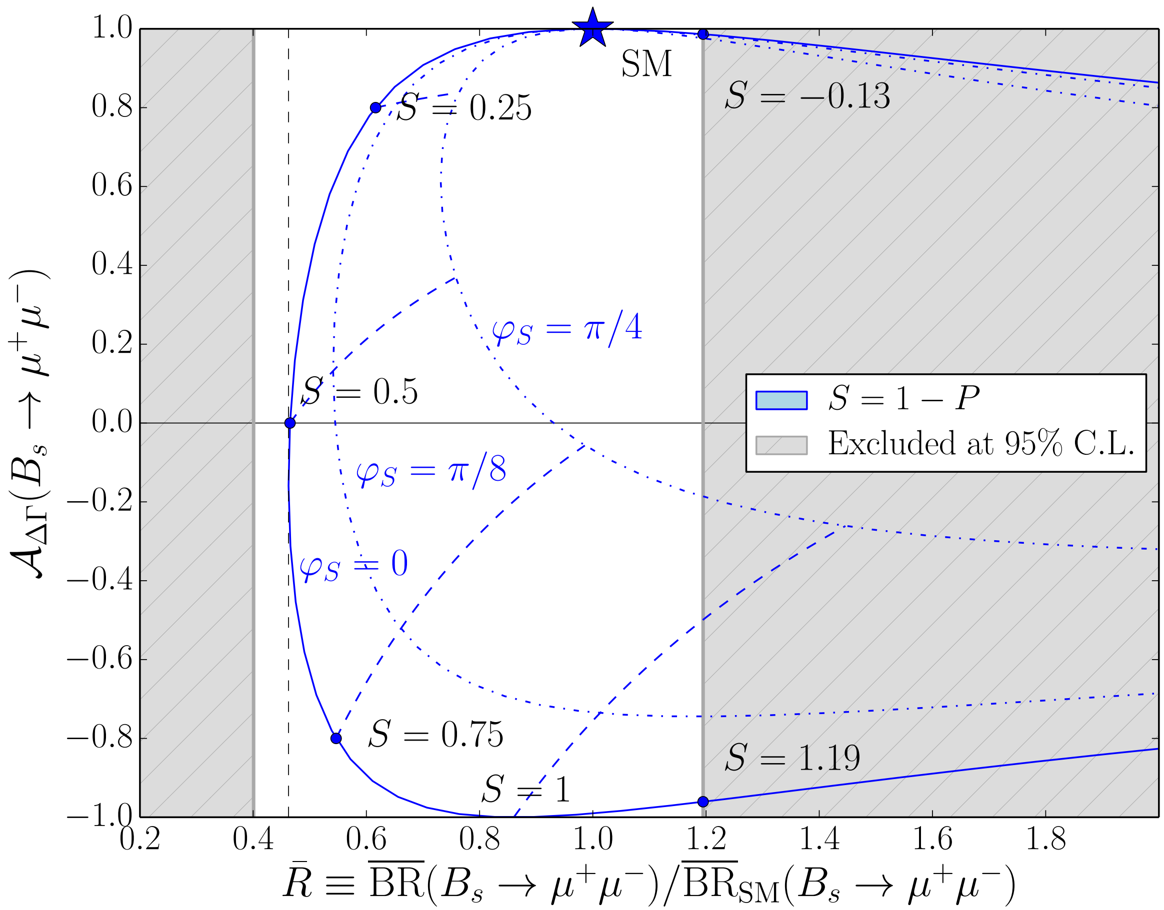


- $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ may differ from its SM value $+1$ without new CP-violating phases.
- $\overline{\rm BR}(B_s \to \mu^+\mu^-) \geq \overline{\rm BR}(B_s \to \mu^+\mu^-)_{\rm SM}$
- Experimental data have already quite some impact here ...

[Example of specific model: 2HDM (scalar H^0 dominance)]

Scenario with $P \pm S = 1$

$\Rightarrow P = 1 + \tilde{P}$, $S = \pm\tilde{P}$ (e.g. $C_S = -C_P$):



- Can access the full range of $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ without new CP-violating phases.
- *Lower bound:* $\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-) \geq \frac{1}{2}(1 - y_s)\,\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}$

[Examples: Decoupled 2HDM/MSSM ($M_{H^0} \approx M_{A^0} \gg M_{h^0}$)]

Detailed Analyses in Specific NP Models

- Tree-Level Neutral Gauge Boson Exchange:

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

$$\mathcal{L}_{\ell\bar{\ell}}(Z') = \left[\Delta_L^{\ell\ell}(Z')(\bar{\ell}\gamma_\mu P_L \ell) + \Delta_R^{\ell\ell}(Z')(\bar{\ell}\gamma_\mu P_R \ell)\right] Z'^{\mu}$$

  - Left-handed Scheme (LHS) with complex $\Delta_L^{bs} \neq 0$ and $\Delta_R^{bs} = 0$
  - Right-handed Scheme (RHS) with complex $\Delta_R^{bs} \neq 0$ and $\Delta_L^{bs} = 0$
  - Left-Right symmetric Scheme (LRS) with complex $\Delta_L^{bs} = \Delta_R^{bs} \neq 0$
  - Left-Right asymmetric Scheme (ALRS) with complex $\Delta_L^{bs} = -\Delta_R^{bs} \neq 0$

- Tree-Level Neutral (Pseudo)Scalar Exchange:

$$\mathcal{L}_{\mathrm{FCNC}}(H) = \left[\Delta_L^{sb}(H)(\bar{s}P_L b) + \Delta_R^{sb}(H)(\bar{s}P_R b)\right] H$$

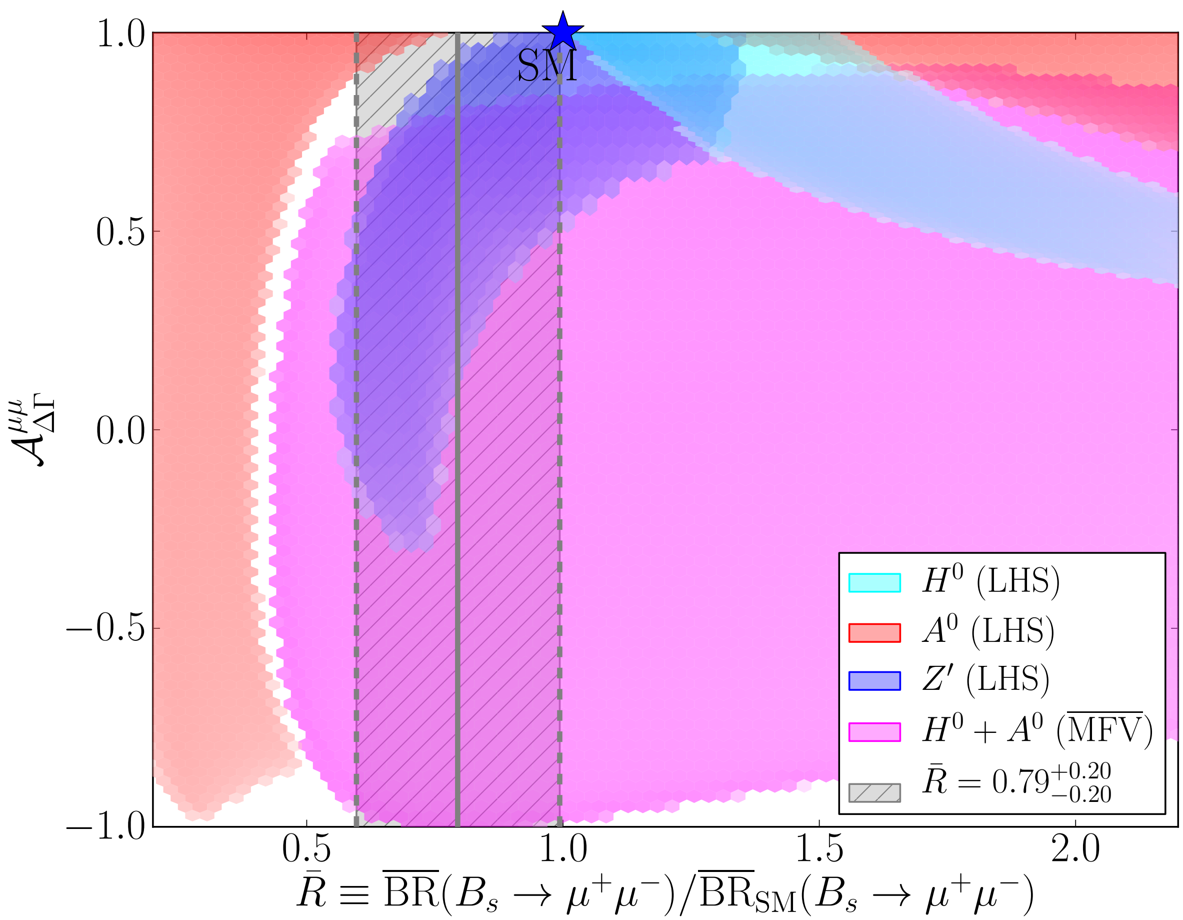
- Tree-Level Neutral Scalar+Pseudoscalar Exchange:

$$\begin{aligned}\mathcal{L}_{\mathrm{FCNC}}(H^0, A^0) = \quad & \left[\Delta_L^{sb}(H^0)(\bar{s}P_L b) + \Delta_R^{sb}(H^0)(\bar{s}P_R b)\right] H^0 \\ & + \left[\Delta_L^{sb}(A^0)(\bar{s}P_L b) + \Delta_R^{sb}(A^0)(\bar{s}P_R b)\right] A^0\end{aligned}$$

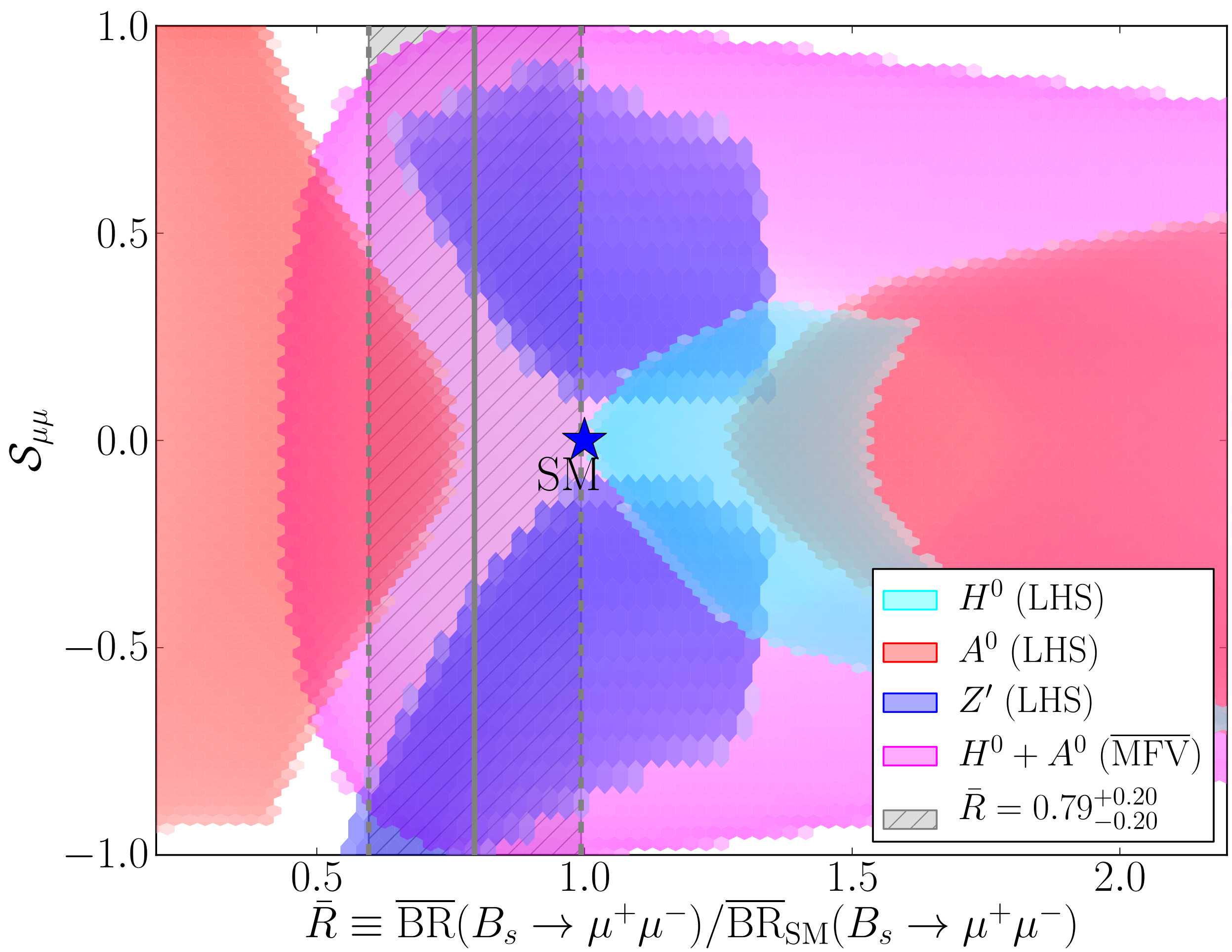
$\rightarrow$ take constraints on B_s^0–$\bar{B}_s^0$ mixing into account [Buras et al. (2013)]

Correlations between Observables

- $\overline{R}$–$\mathcal{A}^{\mu\mu}_{\Delta\Gamma}$ plane: $\rightarrow$ only *untagged* observables



- $\overline{R}$–$\mathcal{S}_{\mu\mu}$ plane: $\rightarrow$ requires *tagging* for CP asymmetry $\mathcal{S}_{\mu\mu}$



– Interesting relation with $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$:

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

Conclusions

Exciting Times for Leptonic Rare B Decays

- BR($B_d \to \mu^+\mu^-$): $\to$ stay tuned ...

  CMS+LHCb: BR $= \left(3.6^{+1.6}_{-1.4}\right) \times 10^{-10}$ while BR$_{\rm SM} = (1.06 \pm 0.09) \times 10^{-10}$

- BR($B_s \to \mu^+\mu^-$): $\to$ evidence at CMS and LHCb:

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

  $\to$ falls into the SM regime although the error is still sizable ...

- Impact of a – seemingly – unrelated topic:

  $\boxed{\text{LHCb has established } \Delta\Gamma_s \neq 0} \Rightarrow$

  - Care has to be taken when dealing with B_s decay branching ratios.
  - "Experimental" vs. "theoretical" branching ratios.
  - $\Delta\Gamma_s$ offers new observables ...

  $\Rightarrow$ $\boxed{\text{enters also the search for NP with } B_s \to \mu^+\mu^-}$

Probing NP with $B_s \to \mu^+\mu^-$

- SM reference value for the comparison with the time-integrated (exp) branching ratio including the $\Delta\Gamma_s$ effects:

$$\boxed{\overline{\mathrm{BR}}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9}}$$ [Bobeth *et al.* (2013)]

- Time-dependent untagged $B_s \to \mu^+\mu^-$ rate:

  ◇ Sizable $\Delta\Gamma_s$ offers access to $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ (effective lifetime $\tau_{\mu\mu}$):

  - New *theoretically clean* observable ($\mathcal{A}_{\Delta\Gamma}^{\mu\mu}|_{\mathrm{SM}} = +1$) to search for NP:
    ◇ in contrast to the BR no dependence on the B_s decay constant F_{B_s}.
  - May reveal NP effects even if the BR is close to the SM prediction:
    ◇ still largely unconstrained (pseudo-)scalar operators $O_{(P)S}$, $O'_{(P)S}$.

- With additional tagging information: $\Rightarrow$ CP asymmetry $\mathcal{S}_{\mu\mu}$

  - Correlations between $\overline{R}$, $\mathcal{A}_{\Delta\Gamma}^{\mu\mu}$ and $\mathcal{S}_{\mu\mu}$ allow us to distinguish between different NP scenarios (effective operators and CP-violating phases).

$\Rightarrow$ *Interesting new studies for the LHC upgrade physics programme!*