On Branching Ratios of B_s Decays and the Search for New Physics in $B_s^0 \to \mu^+\mu^-$

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- Setting the Stage
- B_s Branching Ratios: subtlety due to the width difference $\Delta\Gamma_s \neq 0$
- Key B_s Decay: $B_s^0 \to \mu^+\mu^-$ $\to$ *a new window for New Physics*
- Conclusions

◇ Focus on two recent papers:

K. De Bruyn, R.F., R. Knegjens, P. Koppenburg, M. Merk and N. Tuning:
On Branching Ratio Measurements of B_s Decays [arXiv:1204.1735 [hep-ph]]

K. De Bruyn, R.F., R. Knegjens, P. Koppenburg, M. Merk, A. Pellegrino and N. Tuning:
A New Window for New Physics in $B_s^0 \to \mu^+\mu^-$ [arXiv:1204.1737 [hep-ph]]

Setting the Stage

Weak Decays of B_s Mesons

... encode valuable information about the Standard Model (SM)

- Simplest observables:

  $\diamond$ Branching ratios $\rightarrow$ probability of the considered decay to occur.

- Measurements of B_s branching ratios at hadron colliders:

  – Would require knowledge of the B_s production cross-section (?) ...

  – Hence experimental control channels and the ratio of the $f_s/f_{u,d}$ fragmentation functions, describing the probability that a b quark hadronizes as a $\bar{B}_q$ meson, are required for the extraction of the BR.

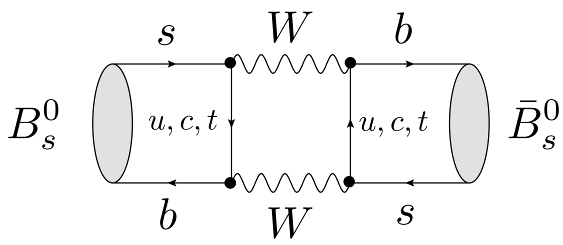
  [Detailed discussion: R.F., N. Serra and N. Tuning, arXiv:1004.3982 [hep-ph]]

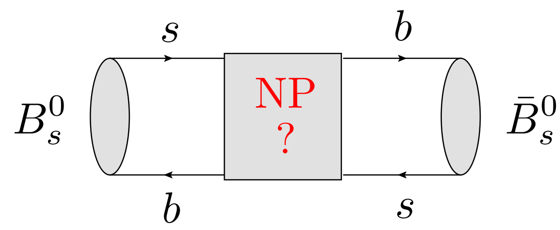
- Measurements of B_s branching ratios at e^+e^- B factories @ $\Upsilon(5S)$:

  – The total number of produced B_s mesons is measured separately and subsequently allows for the extraction of the B_s branching ratio.

  [A. Drutskoy *et al.* (Belle Collaboration), hep-ex/0610003]

News on B_s^0–$\bar{B}_s^0$ Mixing





- 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 [Review: A. Lenz (2012)].
  - Recently established by LHCb [$\to$ talk by Monica Pepe–Altarelli]:

$$y_s \equiv \frac{\Delta\Gamma_s}{2\,\Gamma_s} \equiv \frac{\Gamma_{\rm L}^{(s)} - \Gamma_{\rm H}^{(s)}}{2\,\Gamma_s} = 0.088 \pm 0.014 \quad [\to 6\sigma \text{ effect}]$$

$$\tau_{B_s}^{-1} \equiv \Gamma_s \equiv \frac{\Gamma_{\rm L}^{(s)} + \Gamma_{\rm H}^{(s)}}{2} = (0.6580 \pm 0.0085)\,\text{ps}^{-1}$$

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?

Experiment versus 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)]

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

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

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

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

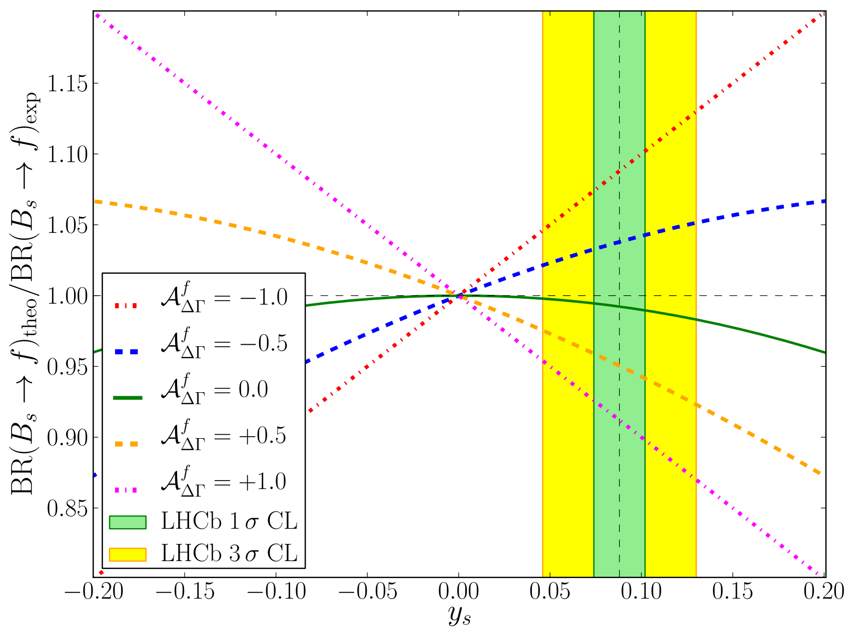
  - By considering $t=0$, the effect of B^0_s–$\bar{B}^0_s$ mixing is "switched off".
  - The advantage of this definition is that it allows a straightforward comparison with the BRs of B^0_d or B^+_u mesons by means of $SU(3)_{\rm F}$.

Conversion of B_s Decay Branching Ratios

- Relation between $\mathrm{BR}\,(B_s \to f)_{\rm theo}$ and the measured $\mathrm{BR}\,(B_s \to f)_{\rm exp}$:

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

- While $y_s = 0.088 \pm 0.014$ has been measured, $\mathcal{A}^f_{\Delta\Gamma}$ depends on the considered decay and generally involves non-perturbative parameters:



⇒ differences can be as large as $\mathcal{O}(10\%)$ for the current value of y_s

- Compilation of theoretical estimates for specific B_s decays:

$B_s \to f$	$\mathrm{BR}(B_s \to f)_{\rm exp}$	$\mathcal{A}^f_{\Delta\Gamma}(\mathrm{SM})$	$\mathrm{BR}\,(B_s \to f)_{\rm theo}\,/\mathrm{BR}\,(B_s \to f)_{\rm exp}$ 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]
$J/\psi K_{\rm S}$	$(3.5 \pm 0.8) \times 10^{-5}$ [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 $\mathrm{BR}\,(B_s \to f)_{\rm exp}$ (see (6)) into $\mathrm{BR}\,(B_s \to f)_{\rm theo}$ (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).

([14]: Amsterdam–Naples Collaboration: R.F., Rob Knegjens & Giulia Ricciardi (2011) $\to$ Rob's talk)

How can we avoid theoretical input? $\to$

- Effective B_s decay lifetimes:

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

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

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

$B_s \to VV$ Decays

- Another application is given by B_s decays into two vector mesons:
  - Examples: $B_s \to J/\psi\phi$, $B_s \to K^{*0}\bar{K}^{*0}$, $B_s \to D_s^{*+}D_s^{*-}$, ...
- Angular analysis of the vector-meson decay products has to be performed to disentangle the CP-even $(0, \parallel)$ and CP-odd $(\perp)$ states (labelled by k):

$$f^{\rm exp}_{VV,k} = \frac{{\rm BR}^{VV,k}_{\rm exp}}{{\rm BR}^{VV}_{\rm exp}}, \quad {\rm BR}^{VV}_{\rm exp} \equiv \sum_k {\rm BR}^{VV,k}_{\rm exp} \;\Rightarrow\; \sum_k f^{\rm exp}_{VV,k} = 1.$$

- Conversion of the "experimental" into the "theoretical" branching ratios:
  - Using *theory info* about $\mathcal{A}^{VV,k}_{\Delta\Gamma} = -\eta_k\sqrt{1 - C^2_{VV,k}}\cos(\phi_s + \Delta\phi_{VV,k})$:

$${\rm BR}^{VV}_{\rm theo} = (1 - y_s^2)\left[\sum_{k=0,\parallel,\perp} \frac{f^{\rm exp}_{VV,k}}{1 + y_s\mathcal{A}^{VV,k}_{\Delta\Gamma}}\right]{\rm BR}^{VV}_{\rm exp}$$

  - Using *effective lifetime measurements:*

$${\rm BR}^{VV}_{\rm theo} = {\rm BR}^{VV}_{\rm exp}\sum_{k=0,\parallel,\perp}\left[2 - (1 - y_s^2)\frac{\tau_k^{VV}}{\tau_{B_s}}\right]f^{\rm exp}_{VV,k}$$

[See also LHCb, arXiv:1111.4183; S. Descotes-Genon, J. Matias & J. Virto (2011)]

Key B_s Decay: $B_s^0 \to \mu^+\mu^-$

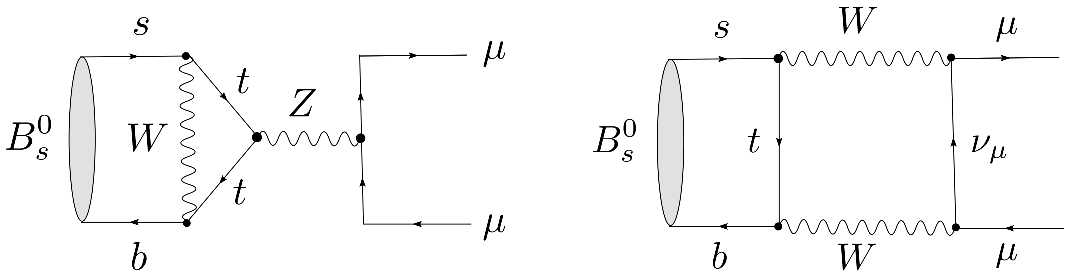
- Upper bounds on the branching ratio are becoming stronger and stronger, thereby approaching the SM prediction ...

- What is the impact of $\Delta\Gamma_s \neq 0$ on these analyses?

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

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

- Only loop contributions in the SM ("penguin" & "box" diagrams):



$\Rightarrow$ strongly suppressed & sensitive to New Physics (NP)

- Hadronic sector: $\to$ simple situation (only B_s-decay constant f_{B_s} enters):

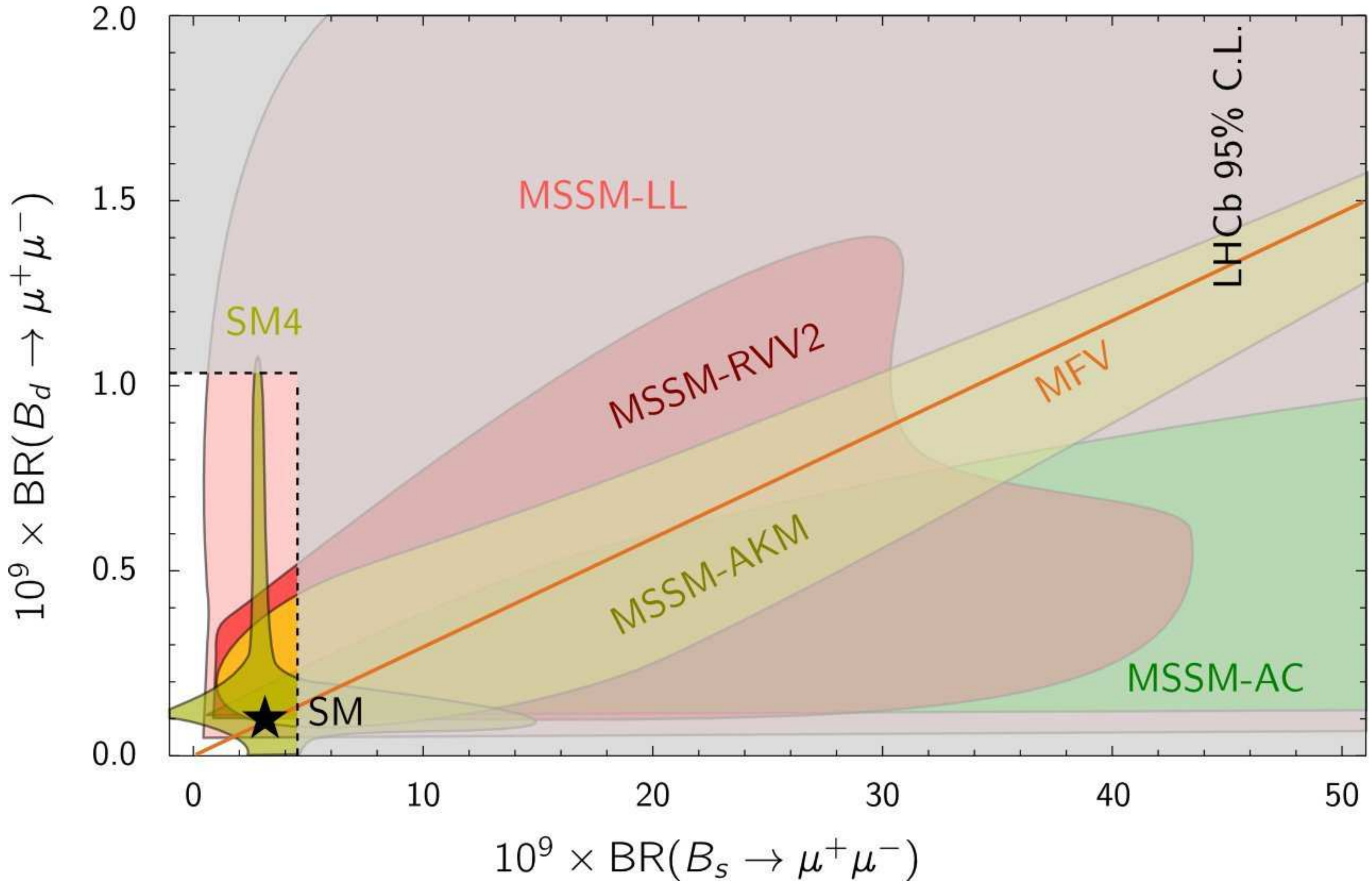
$\Rightarrow$ $B_s^0 \to \mu^+\mu^-$ is one of the cleanest rare B decays

- SM prediction: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$ [A. Buras (2011)]

NP may – in principle – enhance BRs significantly...

[Babu & Kolda, Dedes *et al.*, Foster *et al.*, Carena *et al.*, Isidori & Paradisi, ...]

- Situation in different supersymmetric flavour models, showing also the impact of the recent LHCb upper bounds on $\mathrm{BR}(B_{s,d} \to \mu^+\mu^-)$:



[Andrzej Buras & Jennifer Girrbach (2012)]

The Limiting Factor for the BR($B_s^0 \to \mu^+\mu^-$) Measurement:

- The analysis of $B_s^0 \to \mu^+\mu^-$ relies on normalization channels:

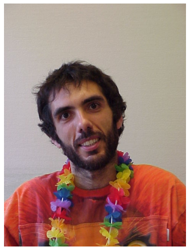
$$\mathrm{BR}(B_s^0 \to \mu^+\mu^-) = \mathrm{BR}(B_q \to X)\frac{\epsilon_X}{\epsilon_{\mu\mu}}\frac{N_{\mu\mu}}{N_X}\frac{f_q}{f_s}$$

  - ϵ factors are total detector efficiencies.
  - N factors denote the observed numbers of events.
  - f_q are *fragmentation functions*, which describe the probability that a b quark will fragment in a B_q meson ($q \in \{u, d, s\}$).

- A closer look shows: *f_s/f_d is the major source of uncertainty:*

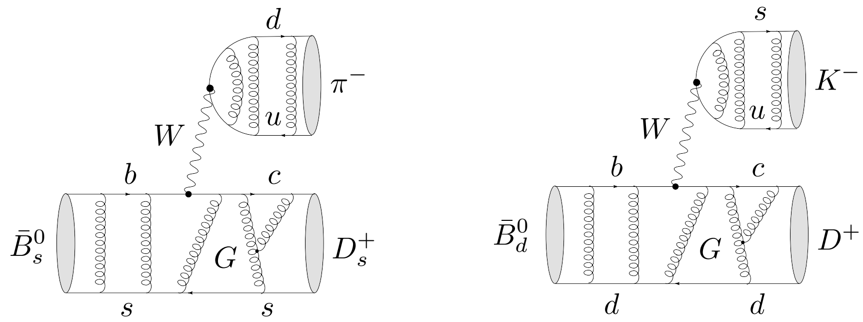
$\Rightarrow$ "boring" non-perturbative, hadronic parameter ...

- New method: $\to$ use non-leptonic B decays to *determine* f_s/f_d @ LHCb



$\Rightarrow$ U-spin-related $\bar{B}_s^0 \to D_s^+\pi^-$, $\bar{B}_d^0 \to D^+K^-$ system:

[R.F., Nicola Serra & Niels Tuning (2010)]



- Prime examples for "factorization": [← Bjorken ('89), Dugan & Grinstein ('91); Beneke, Buchalla, Neubert & Sachrajda ('00); Bauer, Pirjol & Steward ('01); ...]
  - Non-fact. $SU(3)$-breaking corrections: tiny (constrainted through data).
  - Factorizable $SU(3)$-breaking corrections:

    $\rightarrow$ form-factor ratio [QCD sum rule; lattice QCD analyses]:

$$\Rightarrow \textit{ratio of branching ratios can be calculated}$$

$$\Rightarrow \frac{f_s}{f_d} = \underbrace{\frac{N_s}{N_d} \times \frac{\epsilon(\bar{B}^0_d \to D^+K^-)}{\epsilon(\bar{B}^0_s \to D^+_s\pi^-)}}_{\text{experiment}} \times \underbrace{\frac{\mathrm{BR}(\bar{B}^0_d \to D^+K^-)}{\mathrm{BR}(\bar{B}_s \to D^+_s\pi^-)}}_{\text{theory}}$$

- LHCb (using also a variant with $\bar{B}^0_d \to D^+\pi^-$): [PRL (2011)]

$$f_s/f_d = 0.253 \pm 0.017(\text{stat.}) \pm 0.017(\text{syst.}) \pm 0.020(\text{theo.})$$

[excellent agreement with measurements using semileptonic decays]

- Lattice: Fermilab Lattice & MILC [arXiv:1202.6346 [hep-lat] → E. Gamiz's talk].

Experimental Upper Bounds (95% C.L.):

- Tevatron: $\rightarrow$ *"legacy"* ...
  - DØ (2010): BR$(B_s^0 \to \mu^+\mu^-) < 51 \times 10^{-9}$ [$\rightarrow$ talk by A. Ross]
  - CDF (2011): BR$(B_s^0 \to \mu^+\mu^-) < 40 \times 10^{-9}$

- Large Hardon Collider: $\rightarrow$ *future* ...
  - ATLAS (2012): BR$(B_s^0 \to \mu^+\mu^-) < 22 \times 10^{-9}$ [$\rightarrow$ talk by M. Bona]
  - CMS (2012): BR$(B_s^0 \to \mu^+\mu^-) < 7.7 \times 10^{-9}$ [$\rightarrow$ talk by G. Tonelli]
  - LHCb (2012): BR$(B_s^0 \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ [$\rightarrow$ talk by J. Albrecht]

  $\Rightarrow$ *LHCb upper bound is approaching* BR$_{\rm SM} = (3.2 \pm 0.2) \times 10^{-9}$!?

- $\Delta\Gamma_s \neq 0$ has been ignored in these considerations (!):
  - What is the impact for the theoretical interpretation of the data?
  - Can we actually *take advantage* of $\Delta\Gamma_s \neq 0$?

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.

[W. Altmannshofer, P. Paradisi & D. Straub (2011) $\to$ model-independent NP analysis]

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

- Distinguish between the $\mu_L^+\mu_L^-$ and $\mu_R^+\mu_R^-$ helicity configurations:

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

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

- General expression for the decay amplitude [$\eta_L = +1$, $\eta_R = -1$]:

$$A(\bar{B}_s^0 \rightarrow \mu_\lambda^+\mu_\lambda^-) = \langle \mu_\lambda^-\mu_\lambda^+|\mathcal{H}_{\text{eff}}|\bar{B}_s^0\rangle = -\frac{G_F}{\sqrt{2}\pi}V_{ts}^* V_{tb}\alpha$$

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

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

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

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

[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:

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

$\Rightarrow A(B^0_s \to \mu^+_\lambda\mu^-_\lambda) = \langle \mu^-_\lambda\mu^+_\lambda|\mathcal{H}^\dagger_{\rm eff}|B^0_s\rangle$ 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: ("Bonus")

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

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

- Individual observables: $\rightarrow$ *theoretically clean (no dependence on f_{B_s}):*

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

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

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

- Note: $\mathcal{S}_{\mathrm{CP}}\equiv S_\lambda$, $\mathcal{A}_{\Delta\Gamma}\equiv\mathcal{A}_{\Delta\Gamma}^\lambda$ 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:*

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

- Practical comments:
  - It would be most interesting to measure this CP asymmetry since a non-zero value immediately signaled CP-violating NP phases.
  - 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: (→ 1st part of the talk)

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

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

→ *time-integrated untagged rate*, involving

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

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

- Conversion into the "theoretical" branching ratio: → *NP searches:*

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

- $\mathcal{A}_{\Delta\Gamma}$ depends on NP and is hence unknown: $\in [-1,+1] \Rightarrow$ *two options:*
  - Add extra error: $\Delta\mathrm{BR}(B_s \to \mu^+\mu^-)|_{y_s} = \pm y_s \mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}}$.
  - $\mathcal{A}_{\Delta\Gamma}^{\mathrm{SM}} = 1$ gives *new SM reference value* [rescale $\mathrm{BR}_{\mathrm{SM}}$ by $1/(1-y_s)$]:

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}|_{y_s} = (3.5 \pm 0.2)\times 10^{-9}$$

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

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

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

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

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

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

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

  - It is *crucial* that $\mathcal{A}_{\Delta\Gamma}$ does *not* depend on the muon helicity.
  - *Important new measurement for the high-luminosity LHC upgrade:*
    $\Rightarrow$ precision of 5% or better appears feasible for $\tau_{\mu^+\mu^-}$ ...

Constraints on New Physics

- Information from the $B_s \to \mu^+\mu^-$ branching ratio:

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

$$= \left[\frac{1 + y_s \cos 2\varphi_P}{1 - y_s^2}\right] |P|^2 + \left[\frac{1 - y_s \cos 2\varphi_S}{1 - y_s^2}\right] |S|^2 \overset{\text{LHCb}}{<} 1.4$$

  - Unknown CP-violating phases φ_P, $\varphi_S \Rightarrow |P|, |S| \leq \sqrt{(1 + y_s)R} < 1.23$
  - R does not allow a separation of the P and S contributions:

    $\Rightarrow$ *large NP could be present, even if the BR is close to the SM value.*

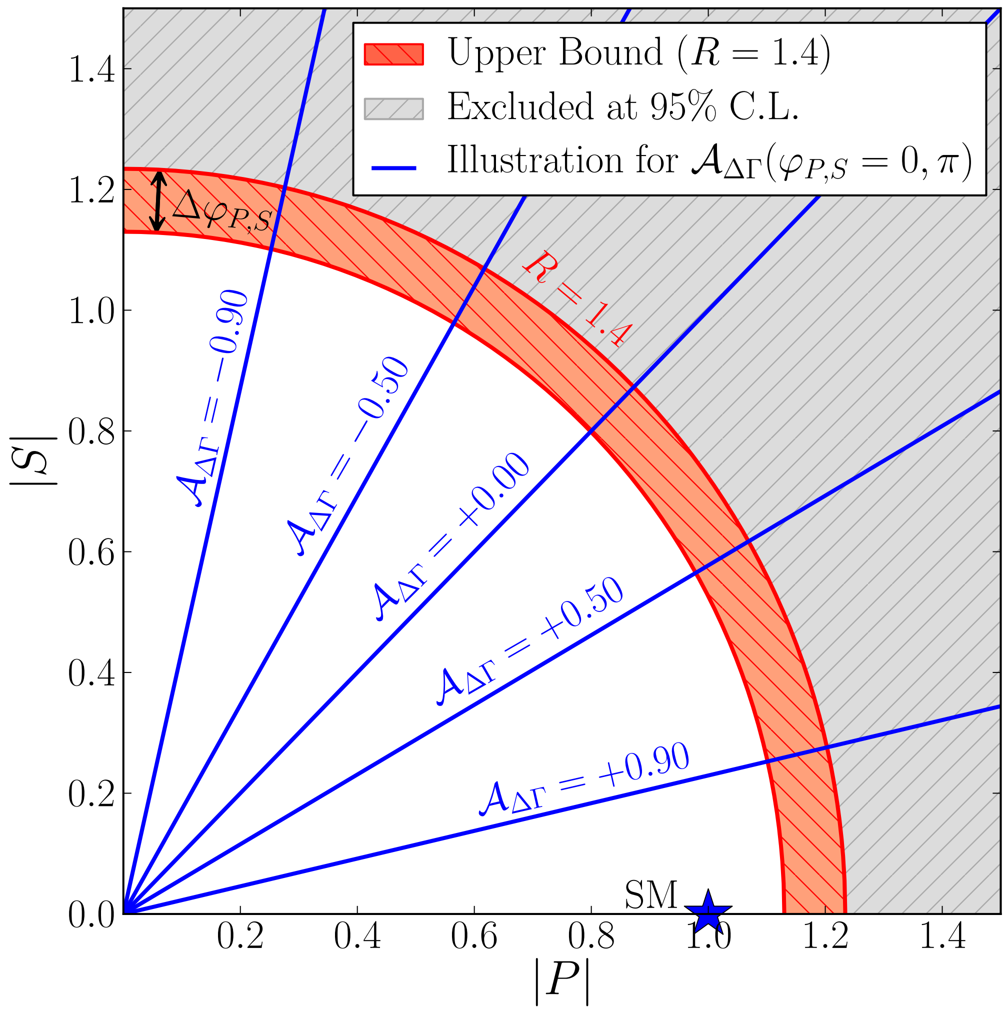
- Further information from the measurement of $\tau_{\mu^+\mu^-}$ yielding $\mathcal{A}_{\Delta\Gamma}$:

$$|S| = |P| \sqrt{\frac{\cos 2\varphi_P - \mathcal{A}_{\Delta\Gamma}}{\cos 2\varphi_S + \mathcal{A}_{\Delta\Gamma}}}$$

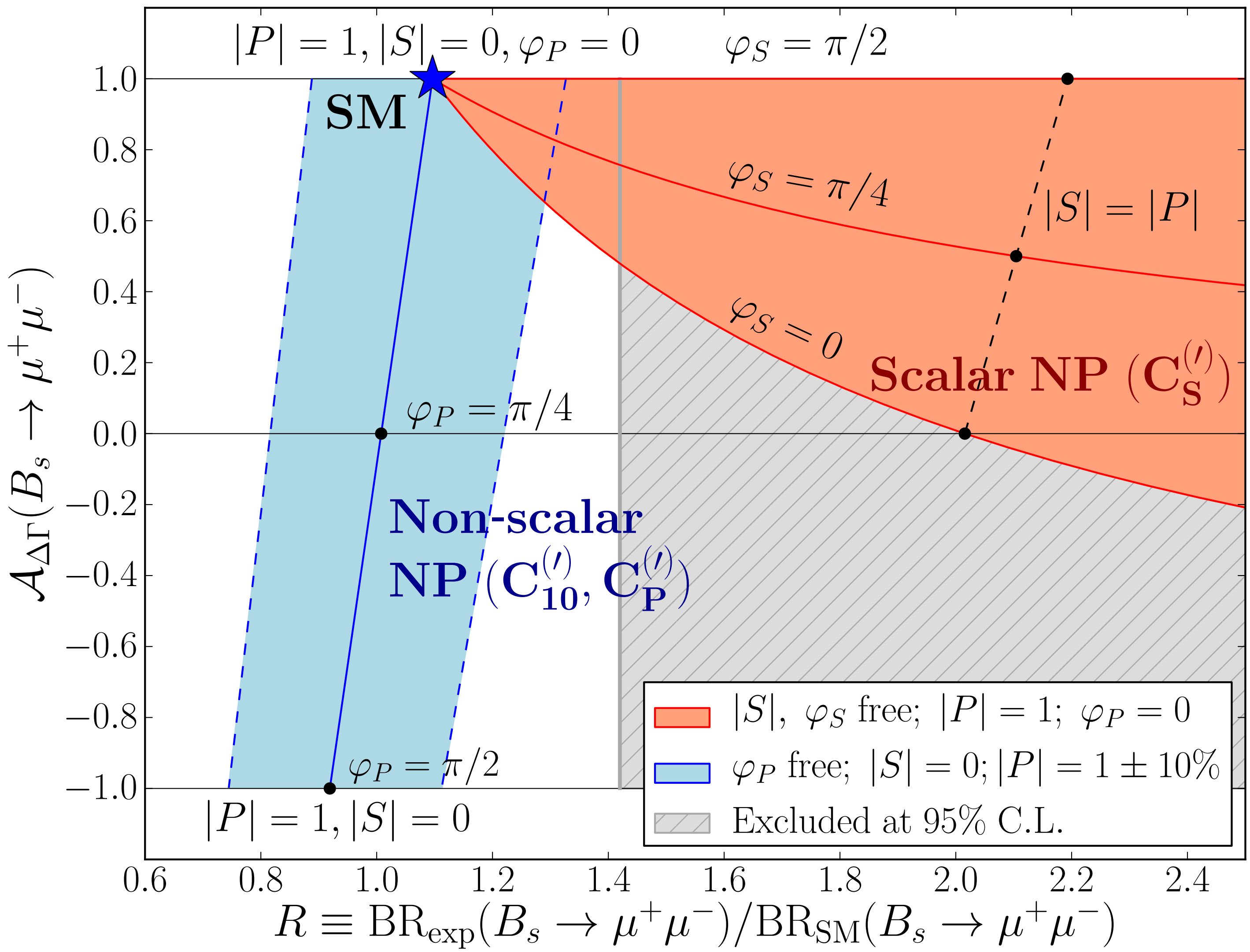
$\Rightarrow$ **offers a new window for New Physics in $B_s \to \mu^+\mu^-$**

How does the situation in NP parameter space look like?

- 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 $\mathcal{A}_{\Delta\Gamma}$:



- Illustration of the allowed regions in the R–$\mathcal{A}_{\Delta\Gamma}$ plane for scenarios with scalar or non-scalar NP contributions:



Conclusions

Subtleties for B_s Branching Ratios

- LHCb has recently established $\Delta\Gamma_s \neq 0$ at the 6σ level: $\Rightarrow$
  - Care has to be taken when dealing with B_s decay branching ratios.
  - Some confusion in the (experimental) literature ...
- Have shown how the measured "experimental" $B_s \to f$ branching ratios can be converted into the "theoretical" $B_s \to f$ branching ratios:
  - Use theoretical input to determine $\mathcal{A}^f_{\Delta\Gamma}$, depending on final state f:
    $\to$ hadronic parameters [use, e.g., $SU(3)_{\rm F}$ $\oplus$ assumptions about NP].
  - Use the measured effective $B_s \to f$ decay lifetime:
    $\to$ preferred avenue using *only data:* $\Rightarrow$ BRs for particle listings
- Examples of specific B_s decays:

$B^0_s \to J/\psi f_0(980)$, $B^0_s \to J/\psi K_{\rm S}$, $B^0_s \to D^-_s\pi^+$, $B^0_s \to K^+K^-$, $B^0_s \to D^+_sD^-_s$, $B^0_s \to J/\psi\phi$, $B^0_s \to K^{(*)0}\bar{K}^{(*)0}$, $B^0_s \to D^{*+}_sD^{*-}_s$, ...

What about $B_s^0 \to \mu^+\mu^-$ in the presence of $\Delta\Gamma_s \neq 0$?

$\to$ have shown that the muon helicity has *not* to be measured:

- The theoretical $B_s^0 \to \mu^+\mu^-$ SM branching ratio has to be rescaled by $1/(1-y_s)$ for the comparison with the experimental branching ratio:

  $\Rightarrow$ *new SM reference:* $\text{BR}(B_s \to \mu^+\mu^-)_{\text{SM}}|_{y_s} = (3.5 \pm 0.2) \times 10^{-9}$

- The $B_s^0 \to \mu^+\mu^-$ decay is a sensitive probe for New Physics:
  - $\mathcal{A}_{\Delta\Gamma} \in [-1, +1] \Rightarrow$ additional relative error of $\pm y_s = \pm 9\%$ for BR_{exp}.
  - y_s can be *included* in the constrains for NP from $\text{BR}(B_s \to \mu^+\mu^-)_{\text{exp}}$.

- The effective lifetime $\tau_{\mu^+\mu^-}$ offers a new observable (yielding $\mathcal{A}_{\Delta\Gamma}$):
  - Allows the extraction of the "theoretical" $B_s \to \mu^+\mu^-$ branching ratio.
  - New *theoretically clean* observable to search for NP: $\mathcal{A}_{\Delta\Gamma}^{\text{SM}} = +1$
    * In contrast to BR_{SM} no dependence on the B_s-decay constant f_{B_s}.
    * May reveal NP effects even if BR is close to the SM prediction: still largely unconstrained (pseudo-)scalar operators $O_{(P)S}$, $O'_{(P)S}$

  $\Rightarrow$ *should be added to the LHC upgrade physics programme!*