Flavour data constraints on New Physics and SuperIso

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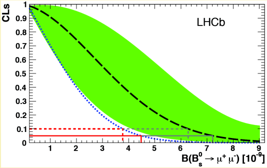
Motivations

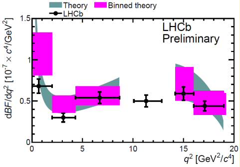
Flavour physics and rare decays in particular are excellent tools to probe New Physics!

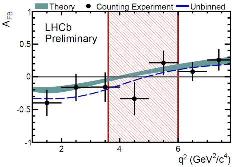
- test quantum structure of the SM at loop level
- investigate the favour and the CP symmetry of the model
  $\to$ test the Minimal Flavour Violation (MFV) hypotheisis
- probe sectors inaccessible to direct searches
- constrain parameter spaces of new physics scenarios

LHCb has also a rich BSM program through indirect searches!

key processes: $B_s \to \mu^+\mu^-$, $B \to K^*\mu^+\mu^-$ and CP violation



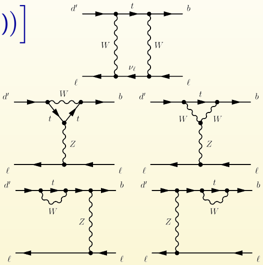




$\to$ Crucial to have a clear estimation of the SM predictions and errors!

BR($B_s \to \mu^+\mu^-$)

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big[\sum_{i=1\cdots 10,S,P} \big(C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu)\big)\Big]$$



Relevant operators:

$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5\ell)$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}^\alpha_L b^\alpha_R)(\bar{\ell}\,\ell), \qquad \mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{s}^\alpha_L b^\alpha_R)(\bar{\ell}\gamma_5\ell)$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3} f_{B_s}^2 \tau_{B_s} m_{B_s}^3 |V_{tb}V_{ts}^*|^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}}$$
$$\times \left\{ \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) |C_S - C'_S|^2 + \left|(C_P - C'_P) + 2\,(C_{10} - C'_{10})\frac{m_\mu}{m_{B_s}}\right|^2 \right\}$$

Very sensitive to new physics, especially for large $\tan\beta$

Experimental results (LHCb): $\mathrm{BR}(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ at 95% C.L.

arXiv:1203.4493

→ Approaching dangerously the SM value!

→ Crucial to have a clear estimation of the SM prediction!

BR($B_s \to \mu^+\mu^-$) - SM prediction

Main source of uncertainty: f_{B_s}

- ETMC-11: **232** $\pm$ **10** MeV
- HPQCD-12: **227** $\pm$ **10** MeV
  HPQCD NR-09: 231 $\pm$ 15 MeV
  HPQCD HISQ-11: 225 $\pm$ 4 MeV
- Fermilab-MILC-11: **242** $\pm$ **9.5** MeV

Our choice: 234 $\pm$ 10 MeV

Most up-to-date input parameters (PDG):

V_{ts}	V_{tb}	m_{B_s}	τ_{B_s}
-0.0403	0.999152	5.3663 GeV	1.472 ps

SM prediction: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.53 \pm 0.38) \times 10^{-9}$

FM, S. Neshatpour, J. Orloff, arXiv:1205.1845

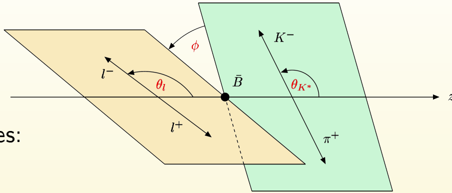
Most important sources of uncertainties:

8% from f_{B_s}
2% from scales
5% from V_{ts}
2% from EW corrections
2% from B_s lifetime
1.3% from top mass

Overall TH uncertainty: $\sim$10%.

$B \to K^*\mu^+\mu^-$ – Angular distributions

Angular distributions



The full angular distribution of the decay $\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-$ ($\bar{K}^{*0} \to K^-\pi^+$) is completely described by four independent kinematic variables: q^2 (dilepton invariant mass squared), θ_ℓ, θ_{K^*}, ϕ

Differential decay distribution:

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_\ell, \theta_{K^*}, \phi)$$

$J(q^2, \theta_\ell, \theta_{K^*}, \phi)$ are written in function of the angular coefficients $J_{1-9}^{s,c}$

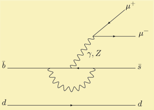
J_{1-9}: functions of the spin amplitudes A_0, $A_\parallel$, $A_\perp$, A_t, and A_S

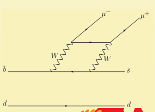
Spin amplitudes: functions of Wilson coefficients and form factors

Main operators:

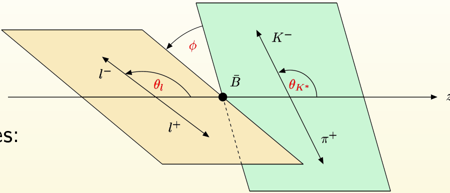
$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell), \quad \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\,\ell), \quad \mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5 \ell)$$





$B \to K^*\mu^+\mu^-$ – Angular distributions



Angular distributions

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$J(q^2, \theta_\ell, \theta_{K^*}, \phi)$ are written in function of the angular coefficients $J^{s,c}_{1-9}$

J_{1-9}: functions of the spin amplitudes A_0, $A_\parallel$, $A_\perp$, A_t, and A_S

Spin amplitudes: functions of Wilson coefficients and form factors

Main operators:

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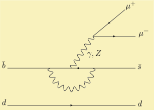
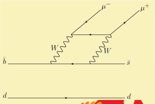




$B \to K^*\mu^+\mu^-$ – Observables

Dilepton invariant mass spectrum: $\dfrac{d\Gamma}{dq^2} = \dfrac{3}{4}\left(J_1 - \dfrac{J_2}{3}\right)$

Forward backward asymmetry:

$$A_{\rm FB}(q^2) \equiv \left[\int_{-1}^{0} - \int_{0}^{1}\right] d\cos\theta_l \, \frac{d^2\Gamma}{dq^2\, d\cos\theta_l} \Big/ \frac{d\Gamma}{dq^2} = \frac{3}{8} J_6 \Big/ \frac{d\Gamma}{dq^2}$$

Forward backward asymmetry zero-crossing: $q_0^2 \simeq -2 m_b m_B \dfrac{C_9^{\rm eff}(q_0^2)}{C_7} + O(\alpha_s, \Lambda/m_b)$

$\to$ fix the sign of C_9/C_7

Polarization fractions:

$$F_L(q^2) = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}, \; F_T(q^2) = 1 - F_L(q^2) = \frac{|A_\perp|^2 + |A_\parallel|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

Transverse asymmetries:

$$A_T^{(1)}(q^2) = \frac{-2\Re(A_\parallel A_\perp^*)}{|A_\perp|^2 + |A_\parallel|^2} \qquad A_T^{(2)}(q^2) = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2}$$

$$A_T^{(3)}(q^2) = \frac{|A_{0L} A_{\parallel L}^* + A_{0R}^* A_{\parallel R}|}{\sqrt{|A_0|^2 |A_\perp|^2}} \qquad A_T^{(4)}(q^2) = \frac{|A_{0L} A_{\perp L}^* - A_{0R}^* A_{\perp R}|}{|A_{0L} A_{\parallel L}^* + A_{0R}^* A_{\parallel R}|}$$

$\to$ **Reduced form factor uncertainties**

$B \to K^*\mu^+\mu^-$ – SM predictions

Observable	SM value	(FF)	(SL)	(QM)	(CKM)	(Scale)
$10^7 \times BR(B \to K^*\mu^+\mu^-)_{[1,6]}$	2.32	± 1.34	± 0.04	${}^{+0.04}_{-0.03}$	${}^{+0.08}_{-0.13}$	${}^{+0.09}_{-0.05}$
$\langle A_{FB}(B \to K^*\mu^+\mu^-)\rangle_{[1,6]}$	-0.06	± 0.04	± 0.02	± 0.01	—	—
$\langle F_L(B \to K^*\mu^+\mu^-)\rangle_{[1,6]}$	0.71	± 0.13	± 0.01	± 0.01	—	—
$q_0^2(B \to K^*\mu^+\mu^-)/\mathrm{GeV}^2$	4.26	± 0.30	± 0.15	${}^{+0.14}_{-0.04}$	—	${}^{+0.02}_{-0.04}$

FM, S. Neshatpour, J. Orloff, arXiv:1205.1845

Main uncertainties from:

- form factors
- $1/m_b$ subleading corrections
- parametric uncertainties (m_b, m_c, m_t)
- CKM matrix elements
- scales

New Physics and Minimal Flavour Violation hypothesis

Minimal Flavour Violation (MFV): Flavour and CP symmetries are broken as in the SM
$\rightarrow$ all flavour- and CP-violating interactions linked to the known structure of Yukawa couplings

Assuming MFV, what are the presently allowed ranges of the Wilson coefficients?

T. Hurth, FM, arXiv:1207.0688

Relevant $\mathcal{O}$perators:

$$\mathcal{O}_7,\ \mathcal{O}_8,\ \mathcal{O}_9,\ \mathcal{O}_{10} \quad \text{and} \quad \mathcal{O}_{S-P} \propto (\bar{s}P_R b)(\bar{\mu}P_L\mu) \equiv \mathcal{O}_0^l$$

NP manisfests itself in the shifts of the individual coefficients with respect to the SM values:

$$C_i(\mu) = C_i^{\rm SM}(\mu) + \delta C_i$$

- $\rightarrow$ Scans over the values of δC_7, δC_8, δC_9, δC_{10}, δC_0^l
- $\rightarrow$ Calculation of flavour observables
- $\rightarrow$ Comparison with experimental results
- $\rightarrow$ Constraints on the Wilson coefficients C_i
- $\rightarrow$ Prediction of flavour observables

Allows to test the MFV hypothesis!

see also: Hurth, Isidori, Kamenik, Mescia, Nucl.Phys. B808 (2009) 326

New Physics and Minimal Flavour Violation hypothesis

→ Global fits of the $\Delta F = 1$ observables obtained by minimization of

$$\chi^2 = \sum_i \frac{\left(O_i^{\rm exp} - O_i^{\rm th}\right)^2}{(\sigma_i^{\rm exp})^2 + (\sigma_i^{\rm th})^2}$$

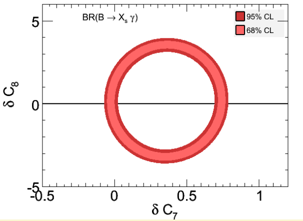
Observables:

- $\mathrm{BR}(B \to X_s\gamma)$
- $\mathrm{BR}(B \to X_d\gamma)$
- $\Delta_0(B \to K^*\gamma)$
- $\mathrm{BR}^{\rm low}(B \to X_s\mu^+\mu^-)$
- $\mathrm{BR}^{\rm high}(B \to X_s\mu^+\mu^-)$

- $\mathrm{BR}(B_s \to \mu^+\mu^-)$
- $\mathrm{BR}^{\rm low}(B \to K^*\mu^+\mu^-)$
- $\mathrm{BR}^{\rm high}(B \to K^*\mu^+\mu^-)$
- $A_{FB}^{\rm low}(B \to K^*\mu^+\mu^-)$
- $A_{FB}^{\rm high}(B \to K^*\mu^+\mu^-)$
- $q_0^2(A_{FB}(B \to K^*\mu^+\mu^-))$
- $F_L^{\rm low}(B \to K^*\mu^+\mu^-)$

New Physics and Minimal Flavour Violation hypothesis

$B \to X_s\gamma$: sensitive to C_7 and C_8



- No linear combination assumed for NP contributions to the electromagnetic and chromomagnetic operators
- Scalar operator strongly restricted by the BR($B_s \to \mu^+\mu^-$) constraint

New Physics and Minimal Flavour Violation hypothesis

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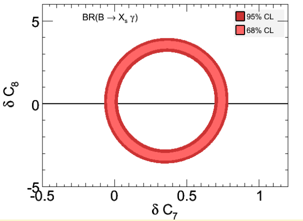
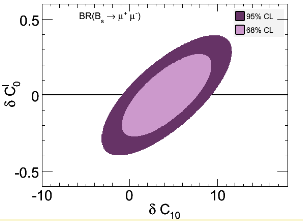


$B_s \to \mu^+\mu^-$: sensitive to C_{10} and C_0^l



- No linear combination assumed for NP contributions to the electromagnetic and chromomagnetic operators
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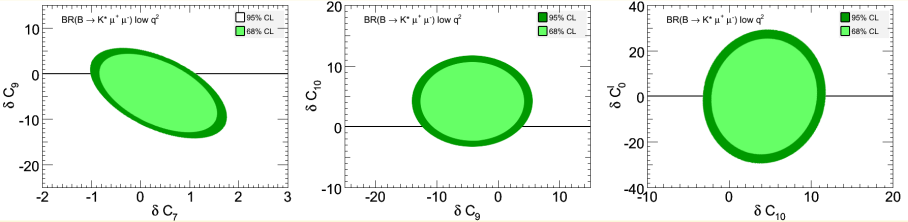
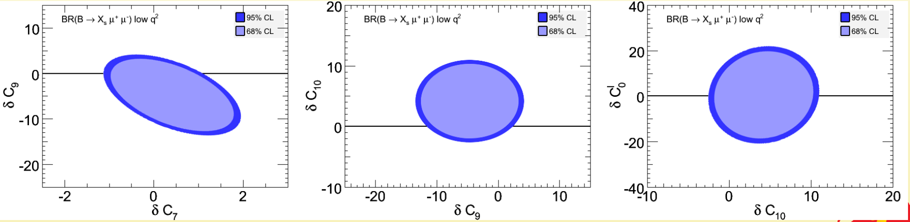
New Physics and Minimal Flavour Violation hypothesis

$B \to K^*\mu^+\mu^-$ exclusive mode:



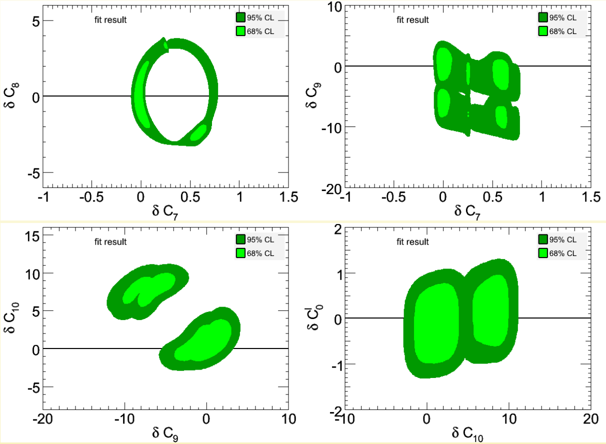
$B \to X_s\mu^+\mu^-$ inclusive mode:



T. Hurth, FM, arXiv:1207.0688

New Physics and Minimal Flavour Violation hypothesis: fits

Before LHCb:



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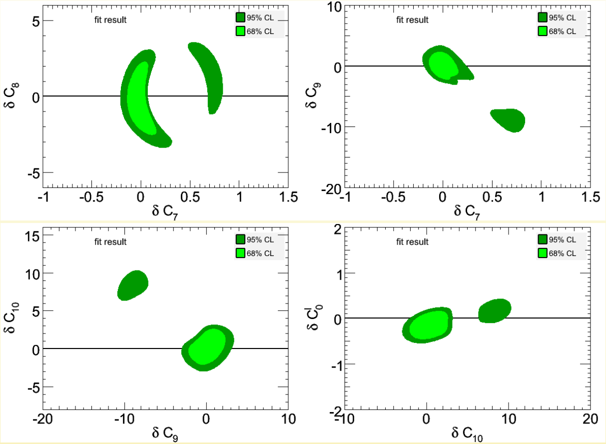


T. Hurth, FM, arXiv:1207.0688

New Physics and Minimal Flavour Violation hypothesis: predictions

Use the allowed ranges for the Wilson coefficients to make predictions for the observables which are not yet measured

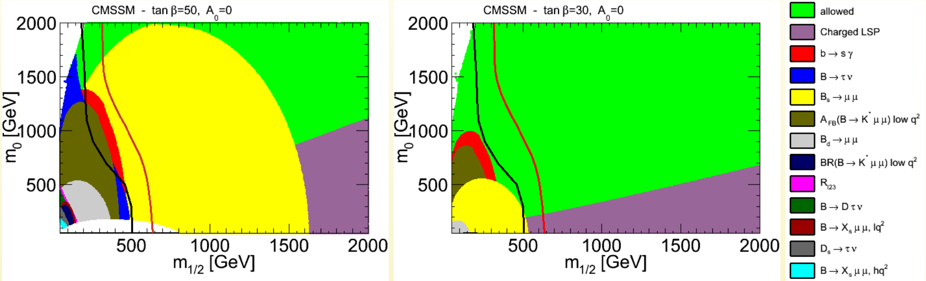
In particular:

- $\mathrm{BR}(B_d \to \mu^+\mu^-) < 0.38 \times 10^{-9}$
  Current LHCb limit: $\mathrm{BR}(B_d \to \mu^+\mu^-) < 1.0 \times 10^{-9}$
- $10^{-7} < \mathrm{BR}(\bar{B} \to X_s\tau^+\tau^-)_{q^2>14.4\,\mathrm{GeV}^2} < 3.7 \times 10^{-7}$
- $q_0^2(A_{FB}(B \to X_s\mu^+\mu^-)) > 1.94\,\mathrm{GeV}^2$
- $B \to K^*\mu^+\mu^-$ transverse asymmetries:
  - $A_T^{(2)} \in [-0.065, -0.022]$
  - $A_T^{(3)} \in [0.34, 0.99]$
  - $A_T^{(4)} \in [0.19, 1.27]$
  - $A_T^{(5)} \in [0.15, 0.49]$

→ **A measurement beyond these results would indicate a new flavour structure!**

Implications for SUSY

Take the example of CMSSM:



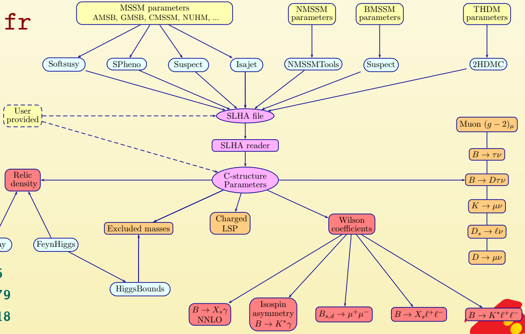
Black line: CMS exclusion limit with 1.1 fb^{-1} data
Red line: CMS exclusion limit with 4.4 fb^{-1} data

FM, arXiv:1205.3099

SuperIso

- public C program
- dedicated to the flavour physics observable calculations
- various models implemented (SM, 2HDM, MSSM, NMSSM, BMSSM,...)
- interfaced to several spectrum calculators
- modular program with a well-defined structure
- complete reference manuals available ($\sim$ 150 pages)

http://superiso.in2p3.fr



FM, Comput. Phys. Commun. 178 (2008) 745
FM, Comput. Phys. Commun. 180 (2009) 1579
FM, Comput. Phys. Commun. 180 (2009) 1718

Conclusion

- Flavour physics plays a very important role in constraining BSM scenarios
- We can test the MFV hypothesis in a generic way
- $B_s \to \mu^+\mu^-$ is a particularly sensive to the scalar contributions and the high $\tan\beta$ regime
- $B \to K^*\mu^+\mu^-$ offers multiple sensitive observables

  $\to$ complementary information!
- Theory uncertainties under control
- With more data constraints will tighten!

Backup

$B \to K^*\mu^+\mu^-$ – Isospin asymmetry

Isospin asymmetry:

Non-factorizable graphs: annihilation or spectator-scattering diagrams

Isospin asymmetry arises when a photon is radiated from the spectator quark

$\to$ depends on the charge of the spectator quark

$\to$ different for charged and neutral B meson decays

$$\frac{dA_I}{dq^2} \equiv \frac{\frac{d\Gamma}{dq^2}(B^0 \to K^{*0}\ell^+\ell^-) - \frac{d\Gamma}{dq^2}(B^- \to K^{*-}\ell^+\ell^-)}{\frac{d\Gamma}{dq^2}(B^0 \to K^{*0}\ell^+\ell^-) + \frac{d\Gamma}{dq^2}(B^- \to K^{*-}\ell^+\ell^-)}$$

The SM is sensitive to C_5 and C_6 at small q^2, but to C_3 and C_4 at larger q^2

Observables: post-LHCb

Observable	Experiment	SM prediction
$\mathrm{BR}(B \to X_s\gamma)$	$(3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$	$(3.08 \pm 0.24) \times 10^{-4}$
$\Delta_0(B \to X_s\gamma)$	$(5.2 \pm 2.6 \pm 0.09) \times 10^{-2}$	$(8.0 \pm 3.9) \times 10^{-2}$
$\mathrm{BR}(B \to X_d\gamma)$	$(1.41 \pm 0.57) \times 10^{-5}$	$(1.49 \pm 0.30) \times 10^{-5}$
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	$< 4.5 \times 10^{-9}$	$(3.53 \pm 0.38) \times 10^{-9}$
$\langle dBR/dq^2(B \to K^*\mu^+\mu^-)\rangle_{q^2\in[1,6]\mathrm{GeV}^2}$	$(0.42 \pm 0.04 \pm 0.04) \times 10^{-7}$	$(0.47 \pm 0.27) \times 10^{-7}$
$\langle dBR/dq^2(B \to K^*\mu^+\mu^-)\rangle_{q^2\in[14.18,16]\mathrm{GeV}^2}$	$(0.59 \pm 0.07 \pm 0.04) \times 10^{-7}$	$(0.71 \pm 0.18) \times 10^{-7}$
$\langle A_{FB}(B \to K^*\mu^+\mu^-)\rangle_{q^2\in[1,6]\mathrm{GeV}^2}$	$-0.18 \pm 0.06 \pm 0.02$	-0.06 ± 0.05
$\langle A_{FB}(B \to K^*\mu^+\mu^-)\rangle_{q^2\in[14.18,16]\mathrm{GeV}^2}$	$0.49 \pm 0.06 \pm 0.05$	0.44 ± 0.10
$q_0^2(A_{FB}(B \to K^*\mu^+\mu^-))$	$4.9^{+1.1}_{-1.3}\ \mathrm{GeV}^2$	$4.26 \pm 0.34\ \mathrm{GeV}^2$
$\langle F_L(B \to K^*\mu^+\mu^-)\rangle_{q^2\in[1,6]\mathrm{GeV}^2}$	$0.66 \pm 0.06 \pm 0.04$	0.72 ± 0.13
$\mathrm{BR}(B \to X_s\mu^+\mu^-)_{q^2\in[1,6]\mathrm{GeV}^2}$	$(1.60 \pm 0.68) \times 10^{-6}$	$(1.78 \pm 0.16) \times 10^{-6}$
$\mathrm{BR}(B \to X_s\mu^+\mu^-)_{q^2>14.4\mathrm{GeV}^2}$	$(4.18 \pm 1.35) \times 10^{-7}$	$(2.19 \pm 0.44) \times 10^{-7}$

T. Hurth, FM, arXiv:1207.0688

Observables: pre-LHCb

Observable	Experiment
$\mathrm{BR}(B \to X_s\gamma)$	$(3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$
$\Delta_0(B \to X_s\gamma)$	$(5.2 \pm 2.6 \pm 0.09) \times 10^{-2}$
$\mathrm{BR}(B \to X_d\gamma)$	$(1.41 \pm 0.57) \times 10^{-5}$
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	$< 5.8 \times 10^{-8}$
$\langle dBR/dq^2(B \to K^*\ell^+\ell^-)\rangle_{q^2\in[1,6]\mathrm{GeV}^2}$	$(0.32 \pm 0.11 \pm 0.03) \times 10^{-7}$
$\langle dBR/dq^2(B \to K^*\mu^+\mu^-)\rangle_{q^2\in[14.18,16]\mathrm{GeV}^2}$	$(0.83 \pm 0.20 \pm 0.07) \times 10^{-7}$
$\langle A_{FB}(B \to K^*\mu^+\mu^-)\rangle_{q^2\in[1,6]\mathrm{GeV}^2}$	$0.43 \pm 0.36 \pm 0.06$
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$\langle F_L(B \to K^*\mu^+\mu^-)\rangle_{q^2\in[1,6]\mathrm{GeV}^2}$	$0.50 \pm 0.30 \pm 0.03$
$\mathrm{BR}(B \to X_s\mu^+\mu^-)_{q^2\in[1,6]\mathrm{GeV}^2}$	$(1.60 \pm 0.68) \times 10^{-6}$
$\mathrm{BR}(B \to X_s\mu^+\mu^-)_{q^2>14.4\mathrm{GeV}^2}$	$(4.18 \pm 1.35) \times 10^{-7}$

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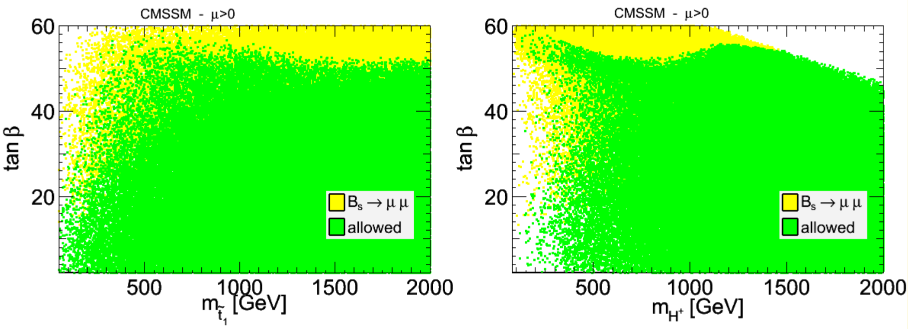
Implications on SUSY – BR($B_s \to \mu^+\mu^-$)

Constraints in CMSSM (all parameters varied)



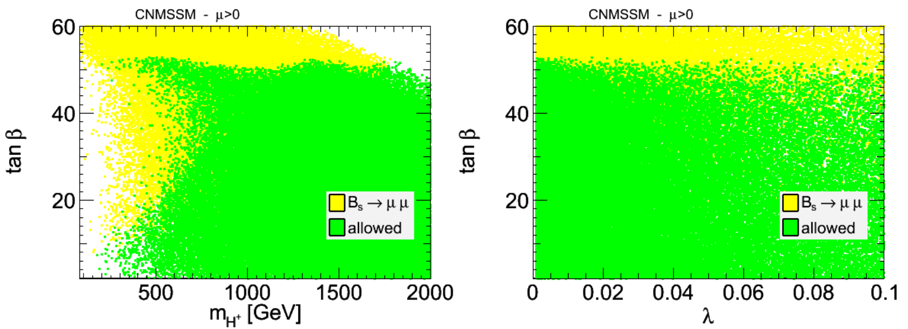
At 95% C.L., including th uncertainty: $\mathrm{BR}(B_s \to \mu^+\mu^-) < 5.0 \times 10^{-9}$

A.G. Akeroyd, F.M., D. Martinez Santos, JHEP 1112 (2011) 088

SuperIso v3.2

Implications on SUSY – BR($B_s \to \mu^+\mu^-$)

Constraints in CNMSSM (all parameters varied)



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SuperIso v3.2

Muon anomalous magnetic moment