BSM with LHCb:
Theory overview of the implications of rare decays

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Outline

- Introduction and motivations
- Flavour observables
  - $B_{s,d} \to \mu^+\mu^-$
  - $B \to K^*\mu^+\mu^-$
- Implications for New Physics
  - Model independent constraints
  - Applications for Supersymmetry
- SuperIso
- Conclusion

Why rare decays?

- sensitivity to new physics effects
- complementary to other searches
- probe sectors inaccessible to direct searches
- test quantum structure of the SM at loop level
- constrain parameter spaces of new physics scenarios
- valuable data already available
- promising experimental situation
- consistency checks with direct observations

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

A multi-scale problem

- new physics: $1/\Lambda_{\rm NP}$
- electroweak interactions: $1/M_W$
- hadronic effects: $1/m_b$
- QCD interactions: $1/\Lambda_{\rm QCD}$

$\Rightarrow$ Effective field theory approach:

separation between low and high energies using Operator Product Expansion

- short distance: Wilson coefficients, computed perturbatively
- long distance: local operators

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

New physics:

- Corrections to the Wilson coefficients: $C_i \to C_i + \delta C_i^{NP}$
- Additional operators: $\sum_j C_j^{NP} \mathcal{O}_j^{NP}$

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$\mathcal{O}$perators

$$\mathcal{O}_7 = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu} \qquad \mathcal{O}'_7 = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu}$$

$$\mathcal{O}_8 = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} T^a P_R b) G^{\mu\nu\, a} \qquad \mathcal{O}'_8 = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} T^a P_L b) G^{\mu\nu\, a}$$

$$\mathcal{O}_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu) \qquad \mathcal{O}'_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \mu)$$

$$\mathcal{O}_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu) \qquad \mathcal{O}'_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_R b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2} m_b (\bar{s} P_R b)(\bar{\mu}\mu) \qquad \mathcal{O}'_S = \frac{e^2}{16\pi^2} m_b (\bar{s} P_L b)(\bar{\mu}\mu)$$

$$\mathcal{O}_P = \frac{e^2}{16\pi^2} m_b (\bar{s} P_R b)(\bar{\mu}\gamma_5 \mu) \qquad \mathcal{O}'_P = \frac{e^2}{16\pi^2} m_b (\bar{s} P_L b)(\bar{\mu}\gamma_5 \mu)$$

Primed operators: opposite chirality to the unprimed ones,
vanish or highly suppressed in the SM

Two main steps:

- Calculating $C_i^{eff}(\mu)$ at scale $\mu \sim M_W$ by requiring matching between the effective and full theories

$$C_i^{eff}(\mu) = C_i^{(0)eff}(\mu) + \frac{\alpha_s(\mu)}{4\pi} C_i^{(1)eff}(\mu) + \cdots$$

- Evolving the $C_i^{eff}(\mu)$ to scale $\mu \sim m_b$ using the RGE:

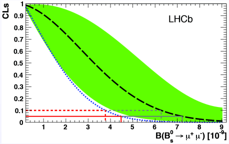
$$\mu \frac{d}{d\mu} C_i^{eff}(\mu) = C_j^{eff}(\mu) \gamma_{ji}^{eff}(\mu)$$

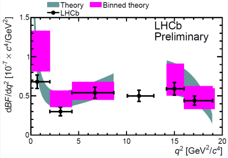
driven by the anomalous dimension matrix $\hat{\gamma}^{eff}(\mu)$:

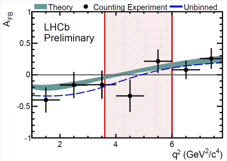
$$\hat{\gamma}^{eff}(\mu) = \frac{\alpha_s(\mu)}{4\pi} \hat{\gamma}^{(0)eff} + \frac{\alpha_s^2(\mu)}{(4\pi)^2} \hat{\gamma}^{(1)eff} + \cdots$$

LHCb recent results:

- $B_{s,d} \to \mu^+\mu^-$
- $B \to K^*\mu^+\mu^-$
  - $\mathrm{BR}(B \to K^*\mu^+\mu^-)$
  - $A_{FB}(B \to K^*\mu^+\mu^-)$
  - $F_L(B \to K^*\mu^+\mu^-)$
  - $S_3(B \to K^*\mu^+\mu^-)$
  - $A_{Im}(B \to K^*\mu^+\mu^-)$
  - $A_{FB_0}(B \to K^*\mu^+\mu^-)$







Other observables:

- $B \to X_{s,d}\gamma$
- $B \to X_s\mu^+\mu^-$
- $B \to \tau\nu$
- $\ldots$

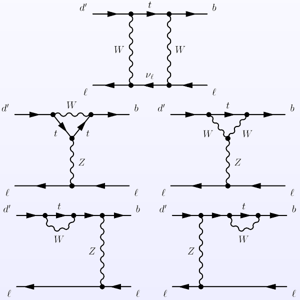
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big[\sum_{i=1\cdots 10,S,P} \big(C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu) \big) \Big]$$

Relevant operators:

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

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

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



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

Very sensitive to new physics, especially for large tan β:

SUSY contributions can lead to an O(100) enhancement over the SM!

Experimental results:

LHCb: $\mathrm{BR}(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ at 95% C.L. arXiv:1203.4493

CMS: $\mathrm{BR}(B_s \to \mu^+\mu^-) < 7.7 \times 10^{-9}$ at 95% C.L. CMS BPH11020

$\to$ Approaching dangerously the SM value!
$\to$ Crucial to have a clear estimation of the 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

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

Most up-to-date input parameters (PDG 2011):

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

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

Most important sources of uncertainties:

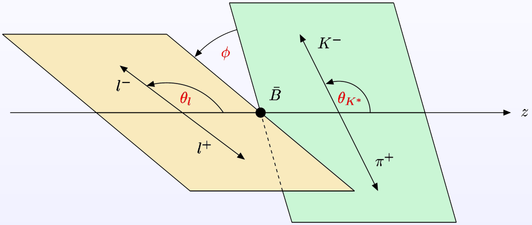
8% from f_{B_s}
2% from EW corrections
2% from scales

2% from B_s lifetime
5% from V_{ts}
1.3% from top mass

Overall TH uncertainty: ∼10%.

Using $f_{B_s} = 225$ MeV and $\tau_{B_s} = 1.425$ ps, one gets: $\mathrm{BR}(B_s \to \mu^+\mu^-) = 3.20 \times 10^{-9}$

Angular distributions



The full angular distribution of the decay $\bar{B}^0 \to \bar{K}^{*0} \ell^+ \ell^-$ with $\bar{K}^{*0} \to K^- \pi^+$ on the mass shell is completely described by four independent kinematic variables:

- q^2: dilepton invariant mass squared
- θ_ℓ: angle between ℓ^- and the $\bar{B}$ in the dilepton frame
- θ_{K^*}: angle between K^- and $\bar{B}$ in the $K^- \pi^+$ frame
- ϕ: angle between the normals of the $K^- \pi^+$ and the dilepton planes

Differential decay distribution:

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

Kinematics: $4m_\ell^2 \leqslant q^2 \leqslant (M_B - m_{K^*})^2$, $-1 \leqslant \cos\theta_\ell \leqslant 1$, $-1 \leqslant \cos\theta_{K^*} \leqslant 1$, $0 \leqslant \phi \leqslant 2\pi$

$J(q^2, \theta_\ell, \theta_{K^*}, \phi)$ 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

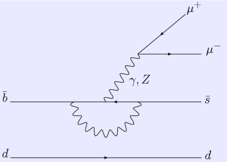
Main operators:

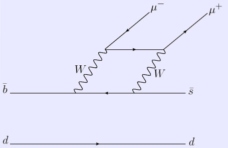
$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$$

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

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

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





Dilepton invariant mass spectrum

$$\frac{d\Gamma}{dq^2} = \frac{3}{4}\left(J_1 - \frac{J_2}{3}\right)$$

Forward backward asymmetry

Difference between the differential branching fractions in the forward and backward directions:

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

→ Reduced theoretical uncertainty

Forward backward asymmetry zero-crossing

→ Reduced form factor uncertainties

$$q_0^2 \simeq -2 m_b m_B \frac{C_9^{\rm eff}(q_0^2)}{C_7} + O(\alpha_s, \Lambda/m_b)$$

→ fix the sign of C_9/C_7

Polarization fractions:

$$F_L(q^2) = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}$$

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

K^* **polarization parameter:**

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

Transverse asymmetries:

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

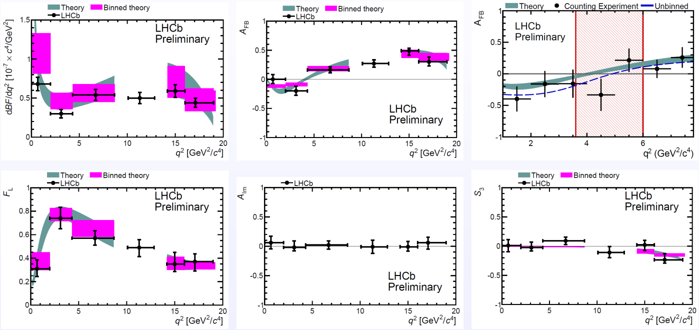
$$A_T^{(3)}(q^2) = \frac{|A_{0L}A_{\parallel L}^* + A_{0R}^* A_{\parallel R}|}{\sqrt{|A_0|^2 |A_\perp|^2}} \qquad A_T^{(4)}(q^2) = \frac{|A_{0L}A_{\perp L}^* - A_{0R}^* A_{\perp R}|}{|A_{0L}A_{\parallel L}^* + A_{0R}^* A_{\parallel R}|}$$

$$A_{Im}(q^2) = -2\,\mathrm{Im}\left(\frac{A_\parallel A_\perp^*}{|A_\perp|^2 + |A_\parallel|^2}\right) \qquad S_3(q^2) = \frac{1}{2}\left(1 - F_L(q^2)\right) A_T^{(2)}(q^2)$$

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	$^{+0.14}_{-0.04}$	—	$^{+0.02}_{-0.04}$

Main uncertainties from:

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



q^2 range (GeV^2/c^4)	dBF/dq^2 ($\times 10^{-7}\,\text{GeV}^{-2}c^4$)	$A_{\rm FB}$	$F_{\rm L}$	$A_{\rm Im}$	$2S_3$
$0.05 < q^2 < 2.00$	$0.68 \pm 0.07 \pm 0.05$	$0.00^{+0.08+0.01}_{-0.07-0.01}$	$0.31^{+0.07+0.03}_{-0.06-0.03}$	$0.06^{+0.11+0.00}_{-0.10-0.03}$	$0.02^{+0.20+0.00}_{-0.21-0.03}$
$2.00 < q^2 < 4.30$	$0.30 \pm 0.05 \pm 0.02$	$-0.20^{+0.08+0.01}_{-0.07-0.03}$	$0.74^{+0.09+0.02}_{-0.08-0.04}$	$-0.02^{+0.10+0.05}_{-0.06-0.01}$	$-0.05^{+0.18+0.05}_{-0.12-0.01}$
$4.30 < q^2 < 8.68$	$0.54 \pm 0.05 \pm 0.05$	$0.16^{+0.05+0.01}_{-0.05-0.01}$	$0.57^{+0.05+0.04}_{-0.05-0.03}$	$0.02^{+0.07+0.01}_{-0.07-0.01}$	$0.18^{+0.13+0.01}_{-0.13-0.01}$
$10.09 < q^2 < 12.89$	$0.50 \pm 0.06 \pm 0.04$	$0.27^{+0.06+0.02}_{-0.06-0.01}$	$0.49^{+0.06+0.03}_{-0.07-0.03}$	$-0.01^{+0.11+0.02}_{-0.11-0.03}$	$-0.22^{+0.20+0.02}_{-0.17-0.03}$
$14.18 < q^2 < 16.00$	$0.59 \pm 0.07 \pm 0.04$	$0.49^{+0.04+0.02}_{-0.06-0.05}$	$0.35^{+0.07+0.07}_{-0.06-0.02}$	$-0.01^{+0.08+0.04}_{-0.07-0.02}$	$0.04^{+0.15+0.04}_{-0.19-0.02}$
$16.00 < q^2 < 19.00$	$0.44 \pm 0.05 \pm 0.03$	$0.30^{+0.07+0.04}_{-0.07-0.01}$	$0.37^{+0.06+0.03}_{-0.07-0.04}$	$0.06^{+0.09+0.03}_{-0.10-0.05}$	$-0.47^{+0.21+0.03}_{-0.10-0.05}$
$1.00 < q^2 < 6.00$	$0.42 \pm 0.04 \pm 0.04$	$-0.18^{+0.06+0.01}_{-0.06-0.02}$	$0.66^{+0.06+0.04}_{-0.06-0.03}$	$0.07^{+0.07+0.02}_{-0.07-0.01}$	$0.10^{+0.15+0.02}_{-0.16-0.01}$

LHCb-CONF-2012-008

Implications

T. Hurth, FM, to appear

Assuming Minimal Flavour Violation (MFV)

What are the presently allowed ranges of the Wilson coefficients?

$\mathcal{O}$perators of interest:

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

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

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

→ Scans over the values of δC_7, δC_8, δC_9, δC_{10}, δC_0^l

→ Calculation of flavour observables

→ Comparison with experimental results

→ Constraints on the Wilson coefficients C_i

see also: Hurth, Isidori, Kamenik, Mescia, Nucl.Phys. B808 (2009) 326
Descotes-Genon, Gosh, Matias, Ramon, JHEP 1106 (2011) 099
Altmannshofer, Paradisi, Straub, JHEP 1204 (2012) 008

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

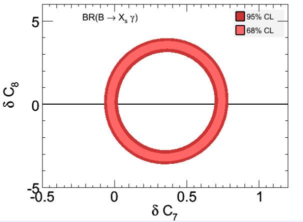
$$\chi^2 = \sum_i \frac{\left(O_i^{\rm exp} - O_i^{\rm th}\right)^2}{(\sigma_i^{\rm exp})^2 + (\sigma_i^{\rm th})^2}$$

Observables:

- $\mathrm{BR}(B \to X_s\gamma)$
- $\mathrm{BR}(B \to X_d\gamma)$
- $\Delta_0(B \to K^*\gamma)$
- $\mathrm{BR}^{\rm low}(B \to X_s\mu^+\mu^-)$
- $\mathrm{BR}^{\rm high}(B \to X_s\mu^+\mu^-)$
- $\mathrm{BR}(B_s \to \mu^+\mu^-)$
- $\mathrm{BR}^{\rm low}(B \to K^*\mu^+\mu^-)$
- $\mathrm{BR}^{\rm high}(B \to K^*\mu^+\mu^-)$
- $A_{FB}^{\rm low}(B \to K^*\mu^+\mu^-)$
- $A_{FB}^{\rm high}(B \to K^*\mu^+\mu^-)$
- $q_0^2(A_{FB}(B \to K^*\mu^+\mu^-))$
- $F_L^{\rm low}(B \to K^*\mu^+\mu^-)$

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

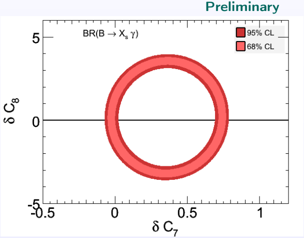
Preliminary



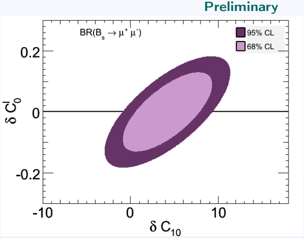
- No linear combination assumed for NP contributions to the electromagnetic and chromomagnetic operators
- Scalar operator strongly restricted by the BR($B_s \to \mu^+\mu^-$) constraint

Model independent constraints on New Physics: individual observables

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



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



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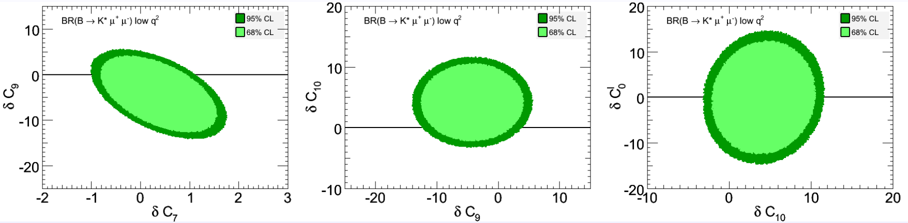
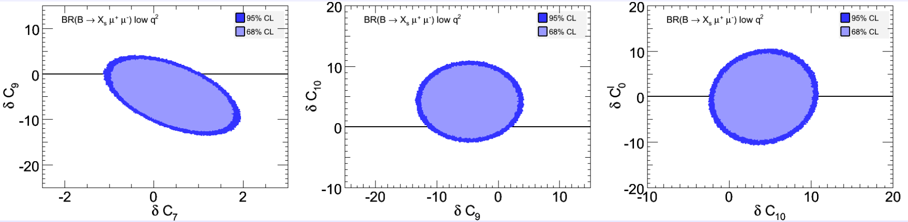
$B \to K^* \mu^+ \mu^-$ exclusive mode

Preliminary



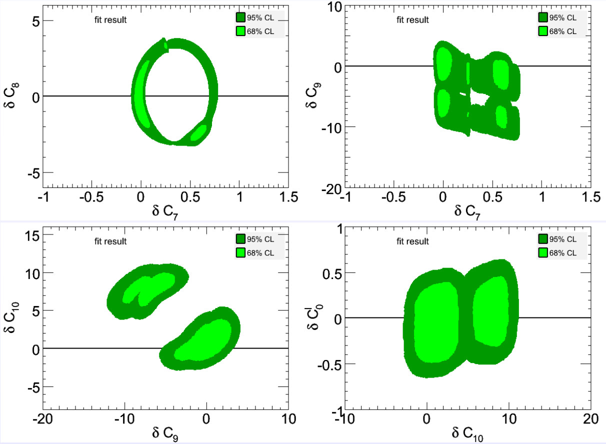
$B \to X_s \mu^+ \mu^-$ inclusive mode

Preliminary

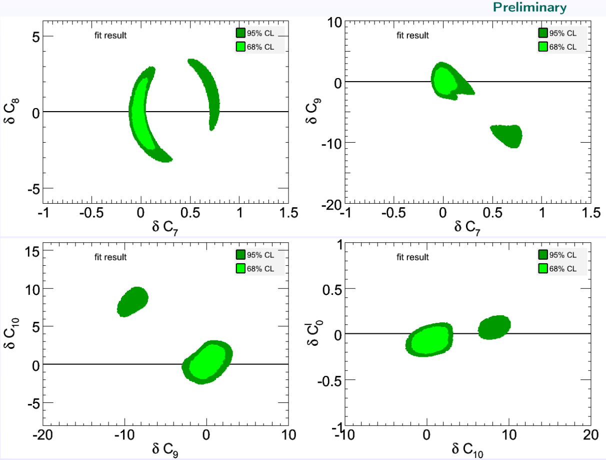


Before LHCb:

Preliminary



After LHCb:


Preliminary
fit result
95% CL
68% CL
δ C8
δ C7
δ C9
δ C10
δ C'0
5
0
-5
10
-10
-20
15
0.5
-0.5
1
-1
-0.5
1.5
20

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

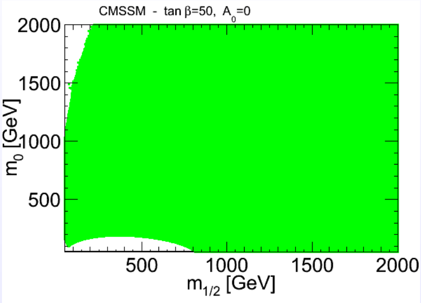
In particular:

- $\mathrm{BR}(B_d \to \mu^+\mu^-) < 0.32 \times 10^{-9}$
  Current LHCb limit: $\mathrm{BR}(B_d \to \mu^+\mu^-) < 1.0 \times 10^{-9}$

- $B \to K^*\mu^+\mu^-$ transverse asymmetries:
  - $A_T^{(2)} \in [-0.068, -0.02]$
  - $A_T^{(3)} \in [0.35, 1.00]$
  - $A_T^{(4)} \in [0.18, 1.30]$
  - $A_T^{(5)} \in [0.15, 0.49]$

$\rightarrow$ **Test of the MFV hypothesis!**

Constraints on Supersymmetry

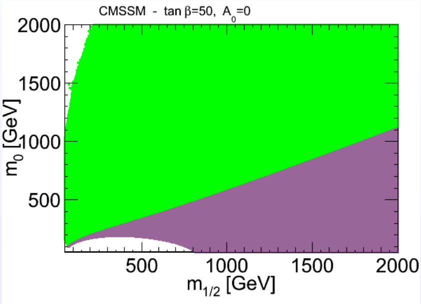


SuperIso v3.3

CMSSM parameter space

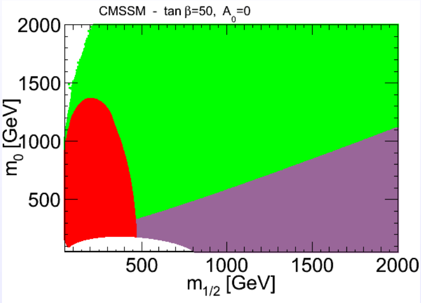
$\tan\beta = 50,\ A_0 = 0$

Constraints on CMSSM



SuperIso v3.3

Stable charged LSP incompatible with cosmology



SuperIso v3.3

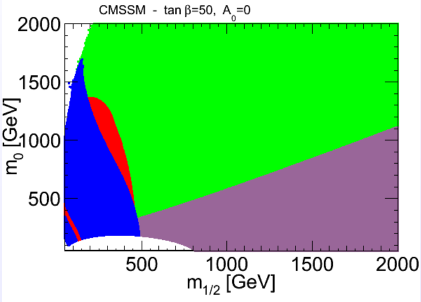
$B \to X_s \gamma$

NNLO calculation

Misiak et al., PRL 98, 022002

Experimental value – HFAG 2011:

$$\mathrm{BR}(\bar{B} \to X_s \gamma) = (3.55 \pm 0.25) \times 10^{-4}$$

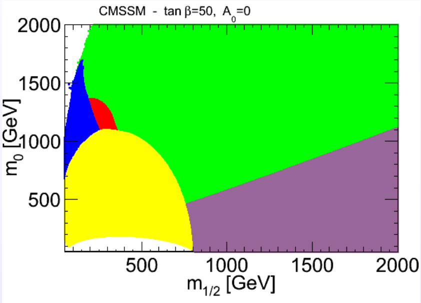


SuperIso v3.3

$$\mathrm{BR}(B \to \tau\nu) = \frac{G_F^2 |V_{ub}|^2}{8\pi} m_\tau^2 f_B^2 m_B \times \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \left|1 - \left(\frac{m_B^2}{m_{H^+}^2}\right) \frac{\tan^2\beta}{1+\epsilon_0 \tan\beta}\right|^2$$

HFAG 2011:

$$\mathrm{BR}(B \to \tau\nu) = (1.64 \pm 0.34) \times 10^{-4}$$



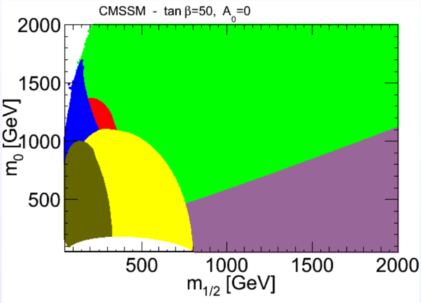
SuperIso v3.3

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

EPS LHCb + CMS combination:

$\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.1 \times 10^{-8}$ at 95% C.L.

Constraints on CMSSM

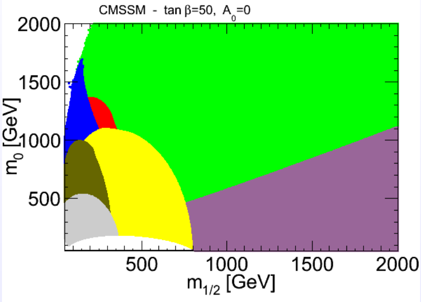


SuperIso v3.3

$$B \to K^* \mu^+ \mu^-$$

In the region $1 < q^2 < 6$ GeV^2 (LHCb):

$$\langle A_{FB}(B \to K^* \mu^+ \mu^-) \rangle = -0.18 \pm 0.06 \pm 0.02$$

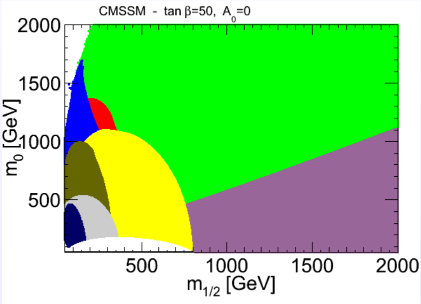


SuperIso v3.3

$$B_d \to \mu^+\mu^-$$

EPS LHCb limit:

$$\mathrm{BR}(B_d \to \mu^+\mu^-) < 5.1 \times 10^{-9} \text{ at 95\% C.L.}$$

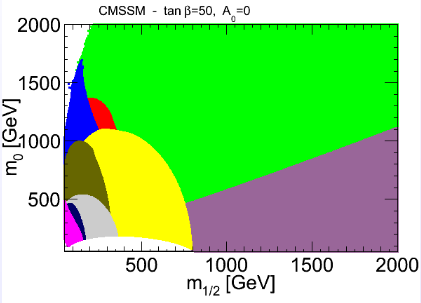


SuperIso v3.3

$$B \to K^* \mu^+ \mu^-$$

In the region $1 < q^2 < 6$ GeV^2 (LHCb):

$$\left\langle \frac{dBR}{dq^2}(B \to K^* \mu^+ \mu^-) \right\rangle = (0.42 \pm 0.04 \pm 0.04) \times 10^{-7}$$



SuperIso v3.3

$$K \to \mu\nu$$

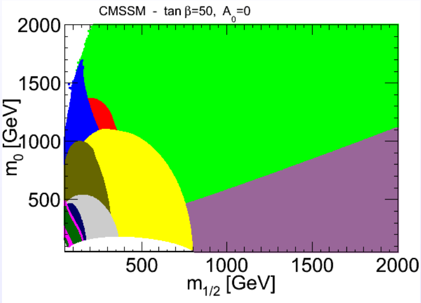
$$R_{\ell 23} = \left| \frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \to 0^+)}{V_{ud}(\pi_{\ell 2})} \right| =$$

$$\left| 1 - \frac{m^2_{K^+}}{M^2_{H^+}} \left(1 - \frac{m_d}{m_s}\right) \frac{\tan^2\beta}{1+\epsilon_0 \tan\beta} \right|$$

Combined experimental and SM constraint:

$$R^{exp/SM}_{l23} = 1.004 \pm 0.014$$

Constraints on CMSSM



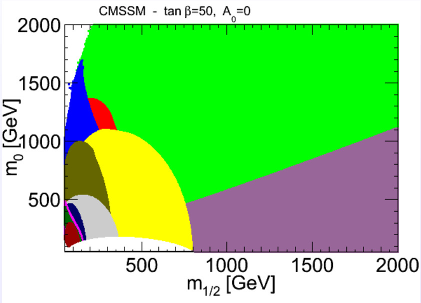
SuperIso v3.3

$$\frac{d\Gamma(B\to D\ell\overline{\nu})}{dw} = \frac{G_F^2|V_{cb}|^2 m_B^5}{192\pi^3}\rho_V(w)\times$$

$$\left[1-\frac{m_\ell^2}{m_B^2}\left|1-\frac{t(w)}{(m_b-m_c)}\frac{m_b}{m_{H^+}^2}\frac{\tan^2\beta}{1+\epsilon_0\tan\beta}\right|^2\rho_S(w)\right]$$

PDG 2011:

$$\frac{\mathrm{BR}(B^-\to D^0\tau^-\nu)}{\mathrm{BR}(B^-\to D^0 e^-\nu)} = 0.416\pm0.117\pm0.052$$

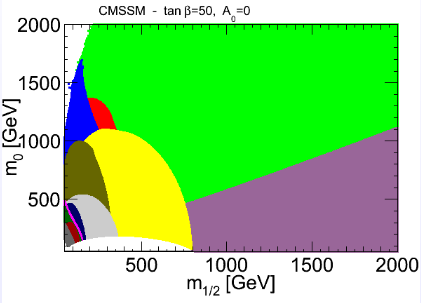


SuperIso v3.3

$B \to X_s \mu^+\mu^-$, high q^2

Experimental value:

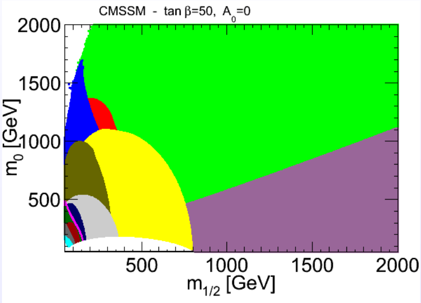
$$\mathrm{BR}(B \to X_s \mu^+\mu^-) = (4.18 \pm 1.35) \times 10^{-7}$$



SuperIso v3.3

$$\mathrm{BR}(D_s \to \ell\nu) =$$
$$\frac{G_F^2}{8\pi}\,|V_{cs}|^2\, f_{D_s}^2\, m_\ell^2\, M_{D_s}\tau_{D_s}\left(1-\frac{m_\ell^2}{M_{D_s}^2}\right)^2$$
$$\times\left[1+\left(\frac{1}{m_c+m_s}\right)\left(\frac{M_{D_s}}{m_{H^+}}\right)^2\right.$$
$$\left.\times\left(m_c-\frac{m_s\tan^2\beta}{1+\epsilon_0\tan\beta}\right)\right]^2$$

HFAG 2011:
$$\mathrm{BR}(D_s \to \tau\nu) = (5.38 \pm 0.32)\times 10^{-2}$$



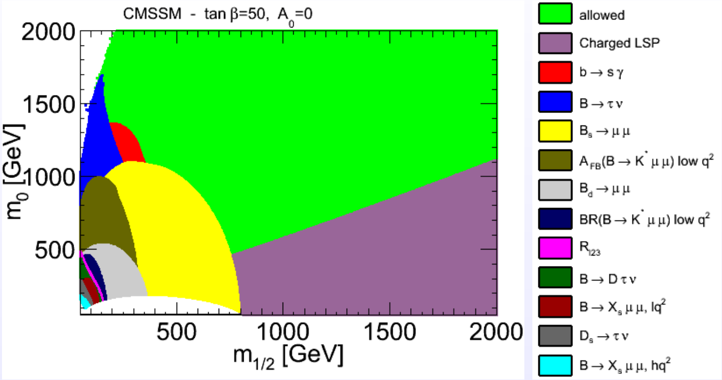
SuperIso v3.3

$B \to X_s \mu^+ \mu^-$, low q^2

Experimental value:

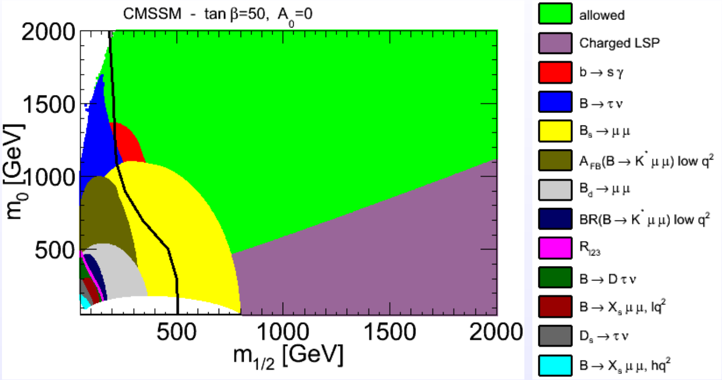
$$\mathrm{BR}(B \to X_s \mu^+ \mu^-) = (1.60 \pm 0.68) \times 10^{-6}$$

Constraints on CMSSM



SuperIso v3.3

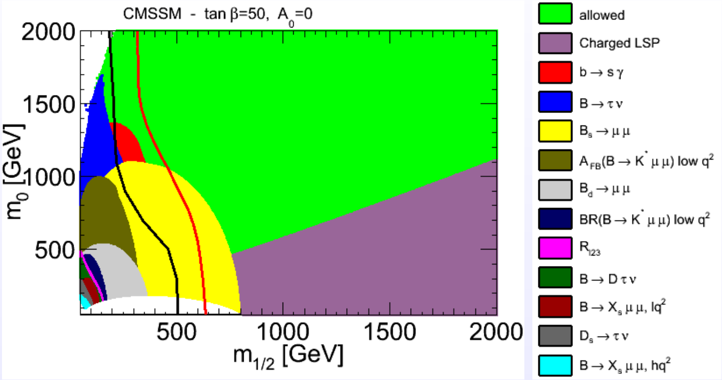
Constraints on CMSSM



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

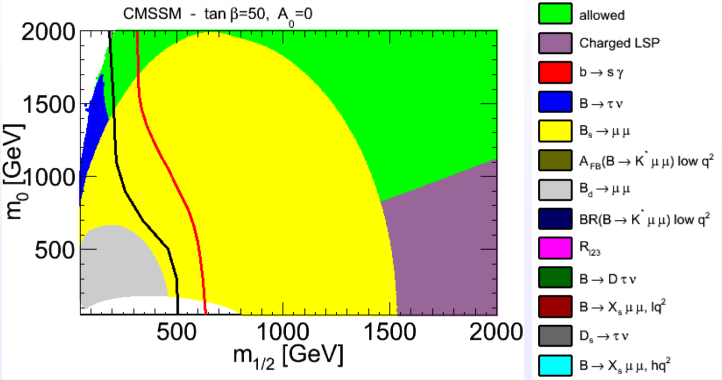
SuperIso v3.3

Constraints on CMSSM



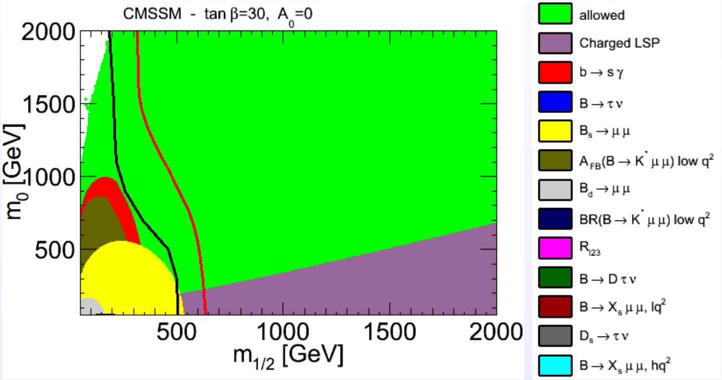
Black line: CMS exclusion limit with 1.1 fb^{-1} data
Red line: CMS exclusion limit with 4.4 fb^{-1} data

SuperIso v3.3



Black line: CMS exclusion limit with 1.1 fb^{-1} data
Red line: CMS exclusion limit with 4.4 fb^{-1} data
New LHCb limits for $\text{BR}(B_s \to \mu^+\mu^-)$ and $\text{BR}(B_d \to \mu^+\mu^-)$

SuperIso v3.3

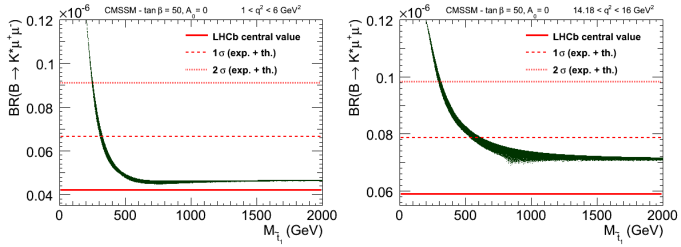


Black line: CMS exclusion limit with 1.1 fb^{-1} data
Red line: CMS exclusion limit with 4.4 fb^{-1} data
New LHCb limits for BR($B_s \to \mu^+\mu^-$) and BR($B_d \to \mu^+\mu^-$)

SuperIso v3.3

BR($B \to K^* \mu^+ \mu^-$) in the low and high q^2 regions:

CMSSM - $\tan\beta = 50$



FM, S. Neshatpour, J. Orloff, arXiv:1205.1845 [hep-ph]

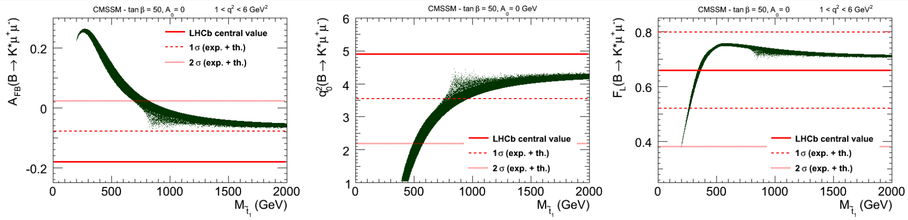
For $m_{\tilde{t}_1} >\sim 300$ GeV, SUSY spread is within the th+exp error

$\to$ Look at other observables (A_{FB}, F_L,...)

$\to$ Reduce both theory and experimental errors.

Other observables of interest:

CMSSM - $\tan \beta = 50$

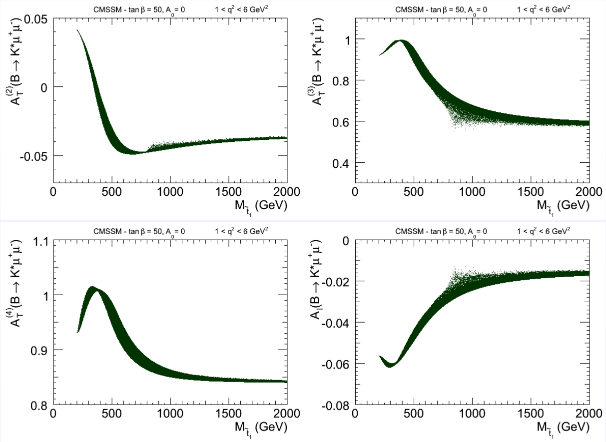


FM, S. Neshatpour, J. Orloff, arXiv:1205.1845 [hep-ph]

A_{FB} in the low q^2 region is especially interesting!

Other observables (not yet measured):

CMSSM - tan $\beta = 50$



FM, S. Neshatpour, J. Orloff, arXiv:1205.1845 [hep-ph]

Going beyond constrained scenarios

- CMSSM useful for benchmarking, model discrimination,...
- However the mass patterns could be more complicated

Phenomenological MSSM (pMSSM)

- The most general CP/R parity-conserving MSSM
- Minimal Flavour Violation at the TeV scale
- The first two sfermion generations are degenerate
- The three trilinear couplings are general for the 3 generations

$\rightarrow$ 19 free parameters

10 sfermion masses, 3 gaugino masses, 3 trilinear couplings, 3 Higgs/Higgsino

A. Djouadi et al., hep-ph/9901246

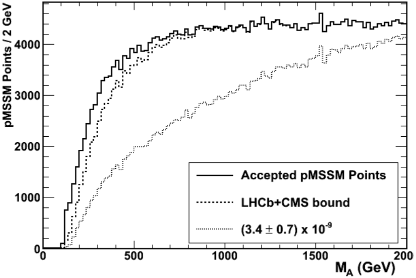
$\rightarrow$ **Interplay between low energy observables and high p_T results**

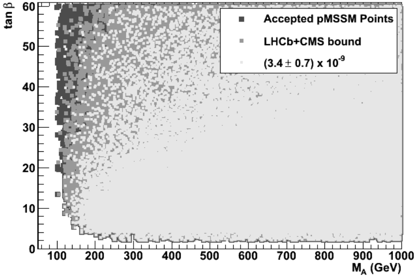
Considering 2 scenarios:

- 2011 bound from LHCb+CMS + estimated th syst:

$$\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.26 \times 10^{-8}$$

- SM like branching ratio with estimated 20% total uncertainty





Light M_A strongly constrained!

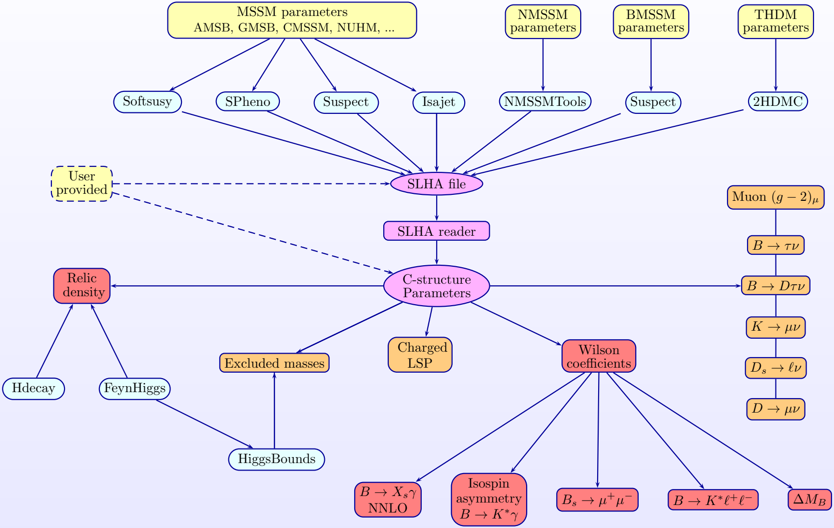
A. Arbey, M. Battaglia, F.M., Eur.Phys.J. C72 (2012) 1847
A. Arbey, M. Battaglia, F.M., Eur.Phys.J. C72 (2012) 1906

- public C program
- dedicated to the flavour physics observable calculations
- various models implemented
- interfaced to several spectrum calculators
- modular program with a well-defined structure
- complete reference manuals available

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

SuperIso



MSSM parameters
AMSB, GMSB, CMSSM, NUHM, ...
NMSSM parameters
BMSSM parameters
THDM parameters
Softsusy
SPheno
Suspect
Isajet
NMSSMTools
Suspect
2HDMC
User provided
SLHA file
SLHA reader
Muon $(g-2)_\mu$
$B \to \tau\nu$
$B \to D\tau\nu$
$K \to \mu\nu$
$D_s \to \ell\nu$
$D \to \mu\nu$
C-structure Parameters
Relic density
Hdecay
FeynHiggs
HiggsBounds
Excluded masses
Charged LSP
Wilson coefficients
$B \to X_s\gamma$ NNLO
Isospin asymmetry $B \to K^*\gamma$
$B_s \to \mu^+\mu^-$
$B \to K^*\ell^+\ell^-$
ΔM_B

Conclusion

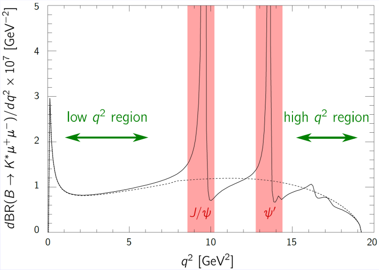
- Flavour physics plays a very important role in constraining BSM scenarios
- $B_s \to \mu^+\mu^-$ is a particularly sensive to the scalar contributions and the high $\tan\beta$ regime
- $B \to K^*\mu^+\mu^-$ offers multiple sensitive observables

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

Backup

$B \to K^* \mu^+ \mu^-$ – Low q^2 vs high q^2

- Low q^2
  - small $1/m_b$ corrections
  - sensitivity to the interference of C_7 and C_9
  - high rate
  - long-distance effects not fully under control
  - non-negligible scale and m_c dependence
- High q^2
  - negligible scale and m_c dependence due to the strong sensitivity to C_{10}
  - negligible long-distance effects of the type $B \to J/\Psi X_s \to X_s + X' \ell^+ \ell^-$
  - sizable $1/m_b$ corrections
  - low rate



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

Model independent constraints on New Physics: 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
$q_0^2(A_{FB}(B \to K^* \mu^+ \mu^-))$	$4.9^{+1.1}_{-1.3}$ GeV^2	4.26 ± 0.34 GeV^2
$\langle F_L(B \to K^* \mu^+ \mu^-)\rangle_{q^2 \in [1,6]\mathrm{GeV}^2}$	$0.66 \pm 0.06 \pm 0.04$	0.71 ± 0.13
$\mathrm{BR}(B \to X_s \mu^+ \mu^-)_{q^2 \in [1,6]\mathrm{GeV}^2}$	$(1.60 \pm 0.68) \times 10^{-6}$	$(1.78 \pm 0.16) \times 10^{-6}$
$\mathrm{BR}(B \to X_s \mu^+ \mu^-)_{q^2 > 14.4\mathrm{GeV}^2}$	$(4.18 \pm 1.35) \times 10^{-7}$	$(2.18 \pm 0.65) \times 10^{-7}$

Observable	Experiment
$\mathrm{BR}(B \to X_s \gamma)$	$(3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$
$\Delta_0(B \to X_s \gamma)$	$(5.2 \pm 2.6 \pm 0.09) \times 10^{-2}$
$\mathrm{BR}(B \to X_d \gamma)$	$(1.41 \pm 0.57) \times 10^{-5}$
$\mathrm{BR}(B_s \to \mu^+ \mu^-)$	$< 5.8 \times 10^{-8}$
$\langle dBR/dq^2(B \to K^* \ell^+ \ell^-)\rangle_{q^2 \in [1,6] \mathrm{GeV}^2}$	$(0.32 \pm 0.11 \pm 0.03) \times 10^{-7}$
$\langle dBR/dq^2(B \to K^* \mu^+ \mu^-)\rangle_{q^2 \in [14.18,16] \mathrm{GeV}^2}$	$(0.83 \pm 0.20 \pm 0.07) \times 10^{-7}$
$\langle A_{FB}(B \to K^* \mu^+ \mu^-)\rangle_{q^2 \in [1,6] \mathrm{GeV}^2}$	$0.43 \pm 0.36 \pm 0.06$
$\langle A_{FB}(B \to K^* \mu^+ \mu^-)\rangle_{q^2 \in [14.18,16] \mathrm{GeV}^2}$	$0.42 \pm 0.16 \pm 0.09$
$\langle F_L(B \to K^* \mu^+ \mu^-)\rangle_{q^2 \in [1,6] \mathrm{GeV}^2}$	$0.50 \pm 0.30 \pm 0.03$
$\mathrm{BR}(B \to X_s \mu^+ \mu^-)_{q^2 \in [1,6] \mathrm{GeV}^2}$	$(1.60 \pm 0.68) \times 10^{-6}$
$\mathrm{BR}(B \to X_s \mu^+ \mu^-)_{q^2 > 14.4 \mathrm{GeV}^2}$	$(4.18 \pm 1.35) \times 10^{-7}$

$$R = \left(\frac{\mathrm{BR}(B_s \to \mu^+ \mu^-)}{\mathrm{BR}(B_u \to \tau\nu)} \right) \Big/ \left(\frac{\mathrm{BR}(D_s \to \tau\nu)}{\mathrm{BR}(D \to \mu\nu)} \right)$$

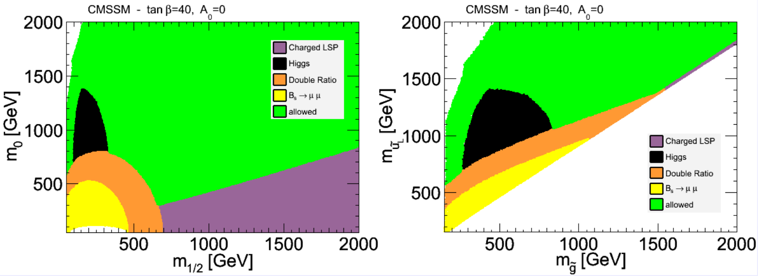
From the form factor and CKM matrix point of view:

$$R \propto \frac{|V_{ts} V_{tb}|^2}{|V_{ub}|^2} \frac{(f_{B_s}/f_B)^2}{(f_{D_s}/f_D)^2} \qquad \text{with:} \qquad \frac{(f_{B_s}/f_B)}{(f_{D_s}/f_D)} \approx 1$$

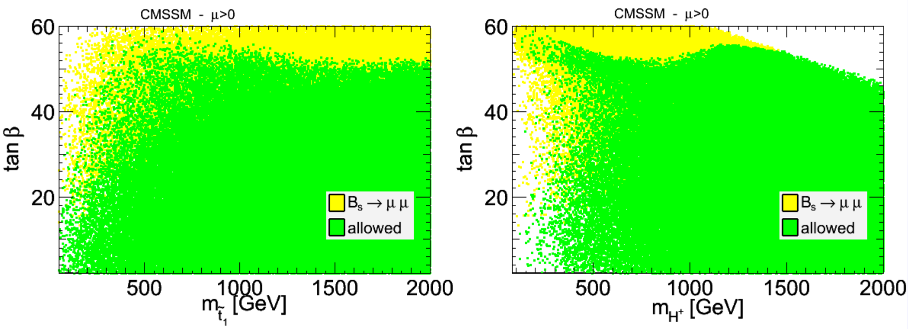
R has no dependence on the decay constants, contrary to each decay taken individually!

- No dependence on lattice quantities
- Interesting for V_{ub} determination
- Interesting for probing new physics
- Promising experimental situation

B. Grinstein, Phys. Rev. Lett. 71 (1993)
A.G. Akeroyd, FM, JHEP 1010 (2010)


CMSSM - tan β=40, A0=0
m0 [GeV]
m1/2 [GeV]
Charged LSP
Higgs
Double Ratio
Bs → μ μ
allowed
CMSSM - tan β=40, A0=0
m_ũL [GeV]
m_g̃ [GeV]
Charged LSP
Higgs
Double Ratio
Bs → μ μ
allowed

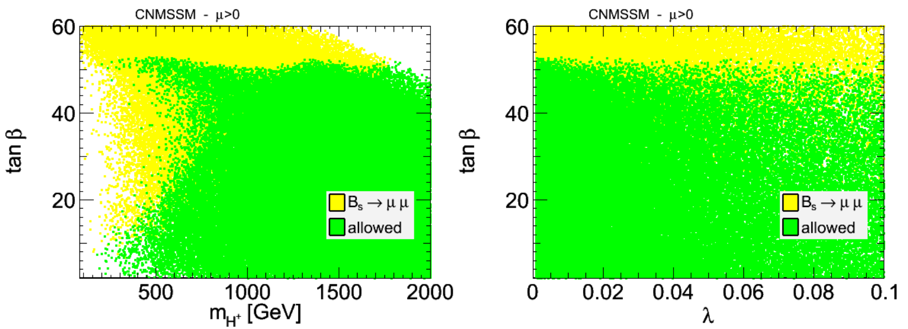
Constraints in CMSSM (all parameters varied)



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

Constraints in CNMSSM (all parameters varied)



A.G. Akeroyd, F.M., D. Martinez Santos, JHEP 1112 (2011) 088
SuperIso v3.2

Muon anomalous magnetic moment