Implications of $B_s \to \mu^+\mu^-$ and $B \to K^*\mu^+\mu^-$ results for supersymmetry

Nazila Mahmoudi

CERN TH & LPC Clermont-Ferrand

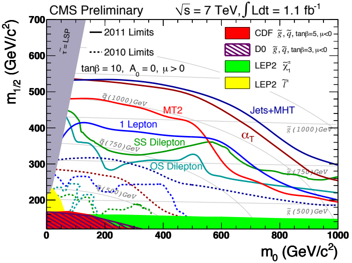
Thanks to: T. Hurth, S. Neshatpour, J. Orloff, A. Arbey, M. Battaglia and A. Djouadi

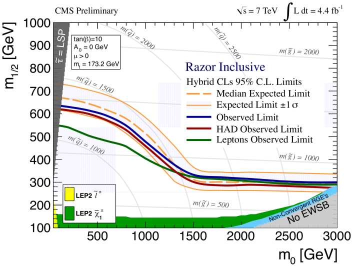
Implications of LHCb measurements and future prospects
CERN, April 16-18, 2012

Search for Supersymmetry

- Direct searches

- Search for SUSY is the main focus of BSM searches in both **ATLAS** and **CMS**
- Strong limits in the constrained SUSY scenarios
- No signal so far...





Search for Supersymmetry

- Direct searches

- Search for SUSY is the main focus of BSM searches in both **ATLAS** and **CMS**
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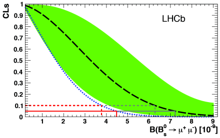
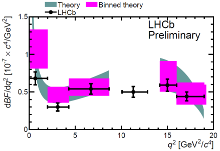
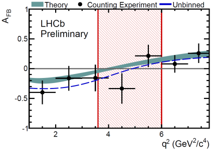
- Indirect searches (flavour)

- **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







While direct searches are only pushing the limits higher, flavour physics can add to the picture substantially!

- Indirect searches (Dark matter, precision tests,...)

Not subject of this talk

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

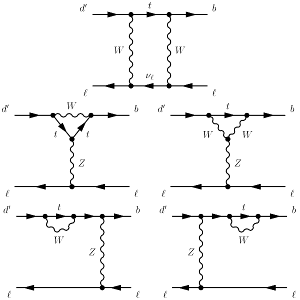
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left[\sum_{i=1\cdots 10,S,P} \left(C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu) \right) \right]$$

Relevant operators:

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

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

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



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

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

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

$\mathrm{BR}(B_s \to \mu^+\mu^-)$

Experimental results:

LHCb: $\mathrm{BR}(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$ at 95% C.L. LHCb-TALK-2012-028

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

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

Main source of uncertainty: f_{B_s}

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

Our choice: 234 ± 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: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.58 \pm 0.36) \times 10^{-9}$

Most important sources of uncertainties:

8% from f_{B_s}
2% from EW corrections
1% from matching scale
2% from μ_b scale

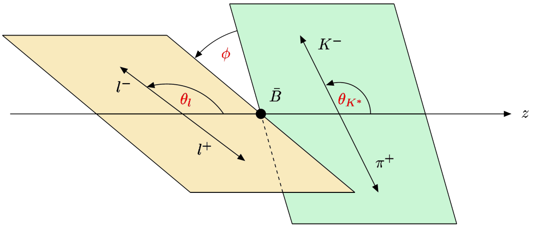
2% from B_s lifetime
5% from V_{ts}
1.3% from top mass

Overall TH uncertainty: 10%.

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

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

Angular distributions



The full angular distribution of the decay $\bar{B}^0 \to \bar{K}^{*0}\ell^+\ell^-$ 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

$B \to K^*\mu^+\mu^-$ – Differential decay distribution

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

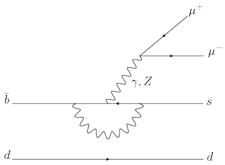
Main operators:

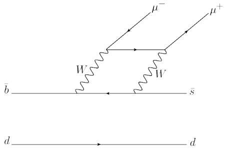
$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$$

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

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

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





$B \to K^*\mu^+\mu^-$ – Observables

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:

$$A_{\rm FB}(q^2) \equiv \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_l \, \frac{d^2\Gamma}{dq^2 \, d\cos\theta_l} \Bigg/ \frac{d\Gamma}{dq^2} = \frac{3}{8} J_6 \Bigg/ \frac{d\Gamma}{dq^2}$$

$\to$ Reduced theoretical uncertainty

Forward backward asymmetry zero-crossing

$\to$ Reduced form factor uncertainties

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

$\to$ fix the sign of C_9/C_7

$B \to K^*\mu^+\mu^-$ – Polarization fractions and transverse asymmetries

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:

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

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

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

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

Isospin asymmetry:

Non-factorizable graphs: annihilation or spectator-scattering diagrams

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

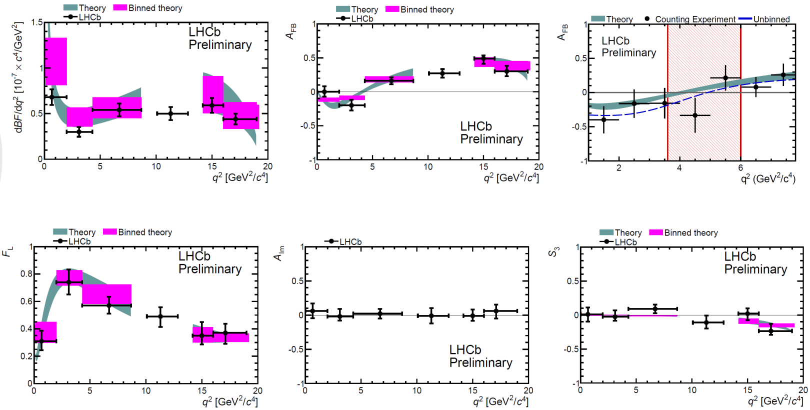
$\rightarrow$ depends on the charge of the spectator quark

$\rightarrow$ 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

$B \to K^*\mu^+\mu^-$ – Experimental results from LHCb



LHCb-CONF-2012-008

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

Most important sources of uncertainty:

For the branching ratio (1 GeV $< q^2 <$ 6 GeV):

57% from form factors

7% from $1/m_b$ sub-leading corrections

2% from parametric uncertainties (m_b, m_c, m_t)

2.5% from scale variations

2.5% from CKM inputs

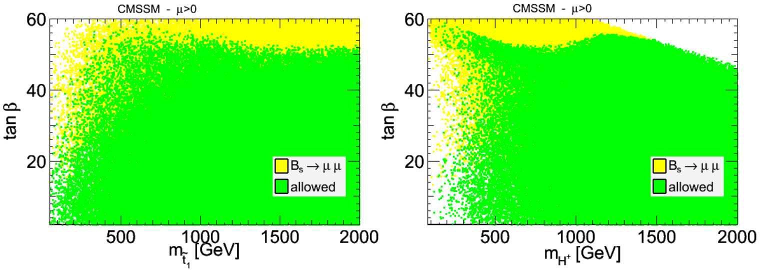
Observable	SM prediction	Experiment
$10^7 \times \langle BR(B \to K^*\mu^+\mu^-)\rangle_{[1,6]}$	0.47 ± 0.27	$0.42 \pm 0.04 \pm 0.04$
$\langle A_{FB}(B \to K^*\mu^+\mu^-)\rangle_{[1,6]}$	-0.06 ± 0.08	$-0.18^{+0.06+0.01}_{-0.06-0.02}$
$\langle F_L(B \to K^*\mu^+\mu^-)\rangle_{[1,6]}$	0.71 ± 0.12	$0.66^{+0.06+0.04}_{-0.06-0.03}$
$q_0^2(B \to K^*\mu^+\mu^-)$ (GeV^2)	4.26 ± 0.33	$4.9^{+1.1}_{-1.3}$

Implications for Supersymmetry:

- Constrained SUSY
- General SUSY

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

Constraints in CMSSM (all parameters varied)

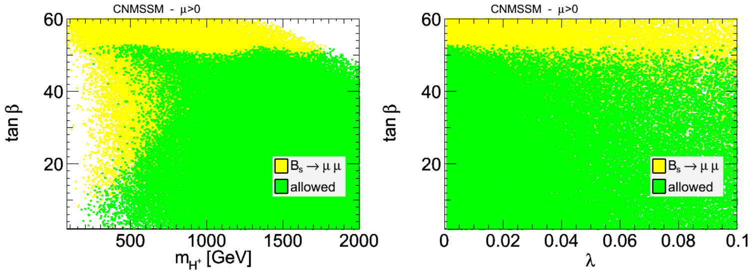


At 95% C.L., including th uncertainty: $\mathrm{BR}(B_s \to \mu^+\mu^-) < 5.0 \times 10^{-9}$

A.G. Akeroyd, F.M., D. Martinez Santos, JHEP 1112 (2011) 088
SuperIso v3.3

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

Constraints in CNMSSM (all parameters varied)

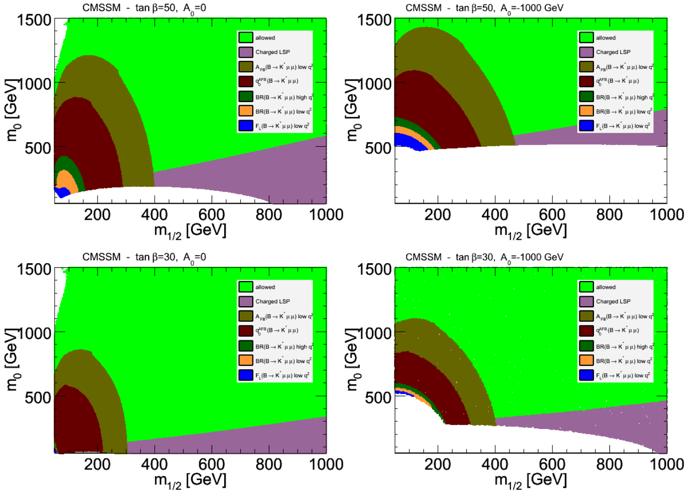


A.G. Akeroyd, F.M., D. Martinez Santos, JHEP 1112 (2011) 088

SuperIso v3.3

Implications – $B \to K^*\mu^+\mu^-$

Constraints in CMSSM (fixed $\tan\beta$ and A_0)

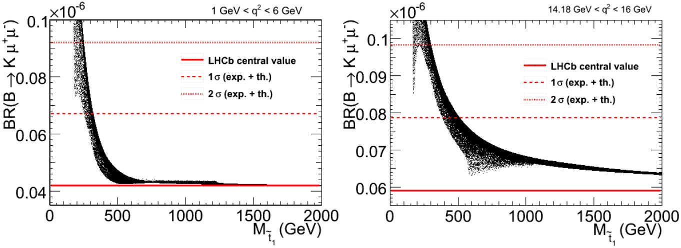


SuperIso v3.3

Implications – $B \to K^*\mu^+\mu^-$

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

CMSSM - $\tan\beta = 50$



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For $m_{\tilde{t}_1} >\sim 400$ GeV, SUSY spread is within the th+exp error

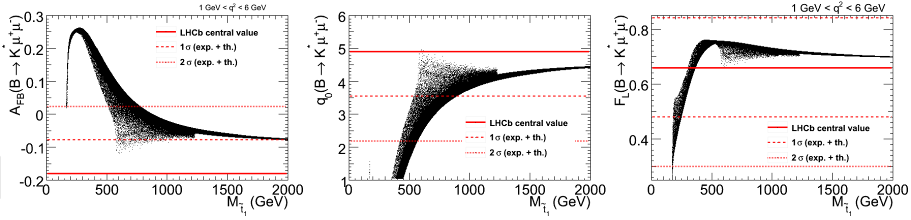
$\to$ Look at other observables (A_{FB}, F_L,...)

$\to$ Reduce both theory and experimental errors.

Implications – $B \to K^*\mu^+\mu^-$

Other observables of interest:

CMSSM - $\tan\beta = 50$



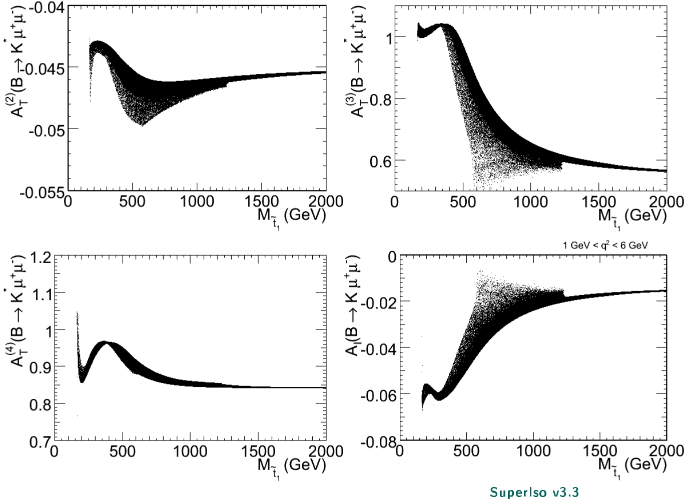
SuperIso v3.3

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

Implications – $B \to K^*\mu^+\mu^-$

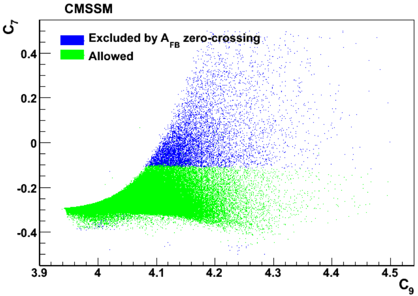
Other observables (not yet measured):

CMSSM - $\tan\beta = 50$



Implications – $B \to K^*\mu^+\mu^-$

A_{FB} zero-crossing in CMSSM (with all parameters varied):

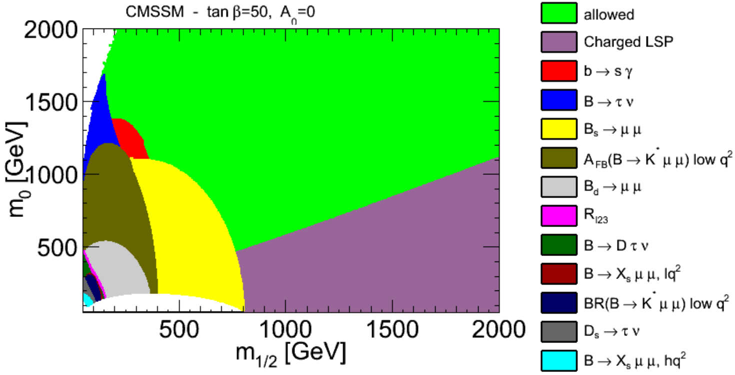


SuperIso v3.3

Sign of C_7 in SUSY is fixed!

Implications

Other rare decays



SuperIso v3.3

Implications

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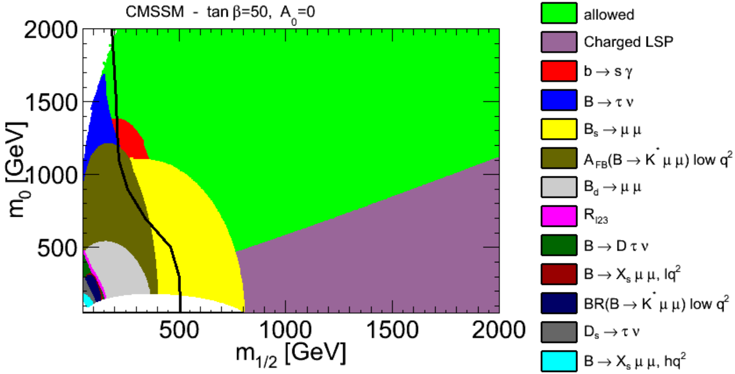

Black line: CMS exclusion limit with 1.1 fb^{-1} data

SuperIso v3.3

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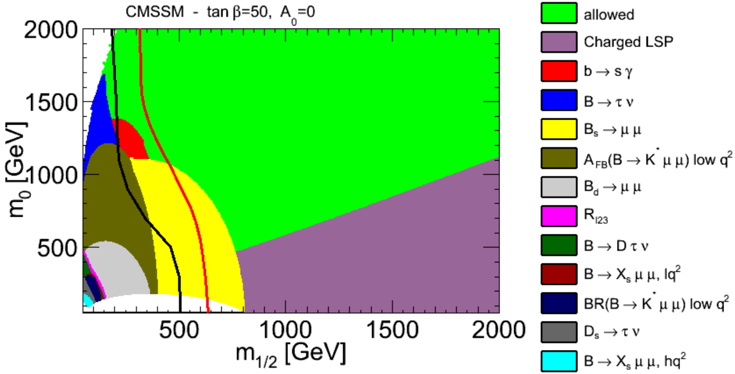
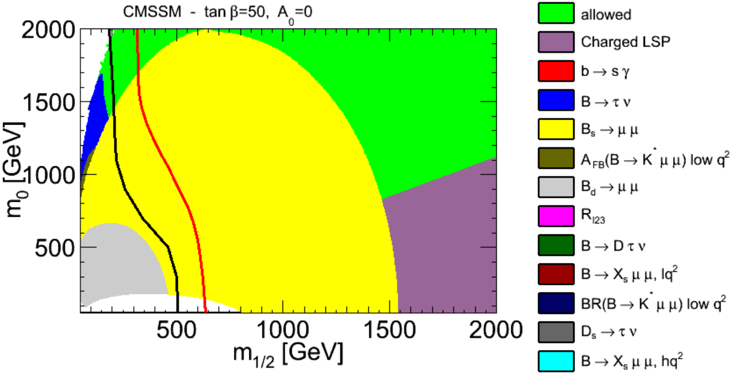


Black line: CMS exclusion limit with 1.1 fb^{-1} data
Red line: CMS exclusion limit with 4.4 fb^{-1} data

SuperIso v3.3

Implications

Other rare decays



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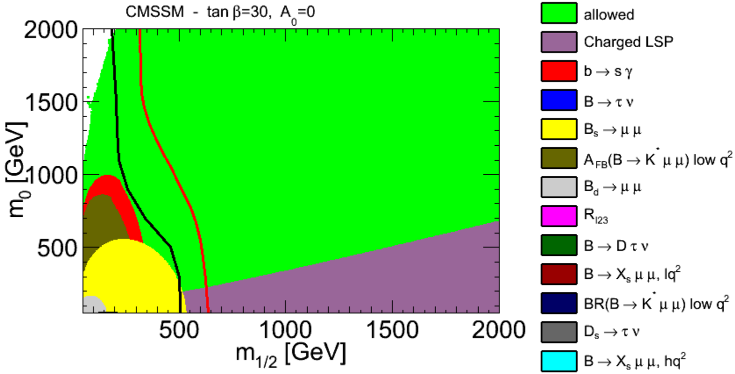
New LHCb limits for $BR(B_s \to \mu^+\mu^-)$ and $BR(B_d \to \mu^+\mu^-)$

SuperIso v3.3

Implications

Other rare decays



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New LHCb limits for $\text{BR}(B_s \to \mu^+\mu^-)$ and $\text{BR}(B_d \to \mu^+\mu^-)$

SuperIso v3.3

General MSSM

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

$\to$ 19 free parameters

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

A. Djouadi, J.-L. Kneur, G. Moultaka, hep-ph/0211331

$\to$ Interplay between low energy observables and high p_t results

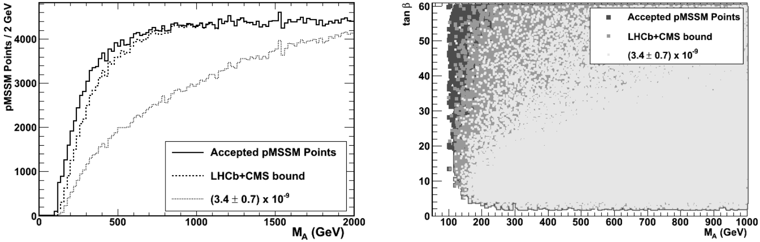
General MSSM – Sensitivity to M_A from BR($B_s \to \mu^+\mu^-$)

Constraints from BR($B_s \to \mu^+\mu^-$):

- 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

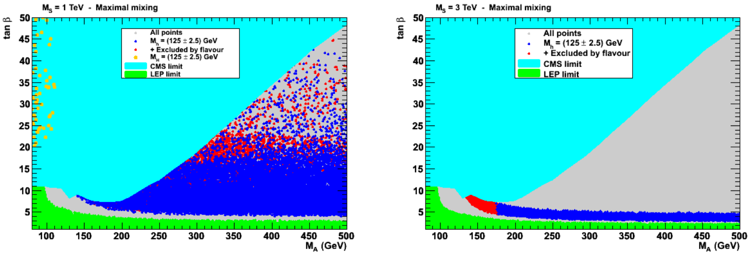


Light M_A strongly constrained!

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

General MSSM – Combined with the Higgs searches

A closer look in the maximal mixing scenario:



Flavour constraints: $b \to s\gamma$, $B \to \tau\nu$ and the new LHCb limit on $B_s \to \mu\mu$

Heavy CP-even SM-like Higgs with $m_H \sim 125$ GeV: excluded by flavour constraints!

$B_s \to \mu\mu$ excludes zones not yet accessible by direct searches!

SuperIso

- Public C program
- dedicated to the flavour physics observable calculations
- Several models implemented:
  General 2HDM, MSSM, NMSSM, BMSSM
- Many flavour observables: $B \to X_s\gamma$, $B_{s,d} \to \mu^+\mu^-$, $B \to \tau\nu$, $B \to D\tau\nu$, $B \to De\nu$, $D_s \to \tau\nu$, $D_s \to \mu\nu$, $K \to \mu\nu$
- Other observables: $(g-2)_\mu$, relic density, ...

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

Imminent release of version 3.3!

Includes $B \to K^*\ell^+\ell^-$ and $B \to X_s\ell^+\ell^-$ observables:

- $B \to X_s\mu^+\mu^-$ (for both high and low q^2):
  - Branching ratio
  - Forward-backward asymmetry (AFB)
  - AFB zero-crossing
- $B \to K^*\mu^+\mu^-$ (for both high and low q^2):
  - Branching ratio
  - Forward-backward asymmetry (AFB)
  - AFB zero-crossing
  - F_L, F_T, α_{K^*}
  - $A_T^{(1)}$, $A_T^{(2)}$, $A_T^{(3)}$, $A_T^{(4)}$, $A_T^{(5)}$
  - A_{Im}
  - $H_T^{(1)}$, $H_T^{(2)}$, $H_T^{(3)}$
  - Isospin asymmetry and zero-crossing

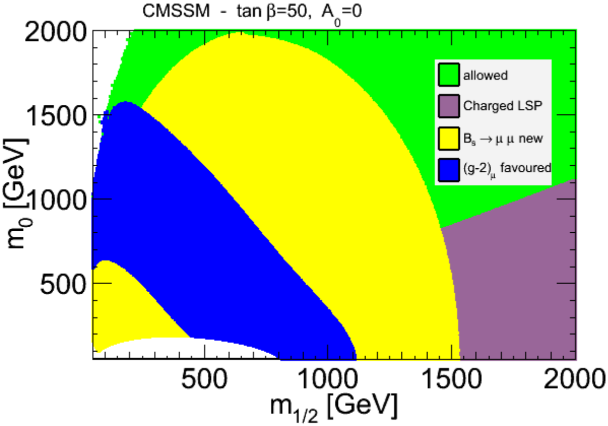
Conclusion

- Interplay between direct and indirect searches is very important and will play a crucial role in the near future
- Many interesting flavour observables available
- The constrained SUSY scenarios are highly constrained
- General MSSM: A lot of viable model points survive, but flavour data can help squeezing the parameter space

Backup

Backup

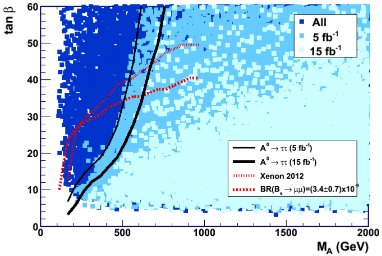
Muon anomalous magnetic moment



General MSSM – Combined with the Higgs searches

Squeeze even more the parameter space by combining with:

- Direct SM-like Higgs searches
- Limit from $A \to \tau^+\tau^-$
- Constraints from $\mathrm{BR}(B_s \to \mu^+\mu^-)$
- Dark matter direct detection constraints (XENON)



$123 < M_h < 127$ GeV

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

General MSSM – Combined with the Higgs searches

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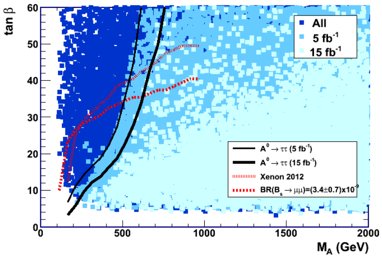

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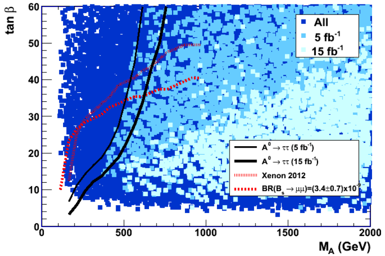
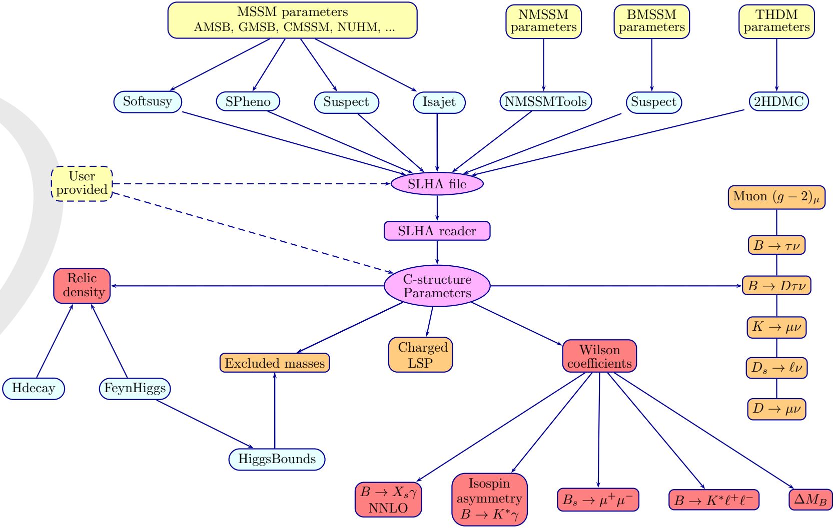


imposing in addition the h rates

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

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
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
Muon $(g-2)_\mu$
$B \to \tau\nu$
$B \to D\tau\nu$
$K \to \mu\nu$
$D_s \to \ell\nu$
$D \to \mu\nu$