Rare decays and other future prospects in flavour physics

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Implications of LHC results for TeV-scale physics – WG3 meeting

CERN, December 9th, 2011

Motivations

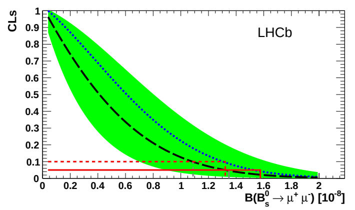
Indirect searches for New Physics

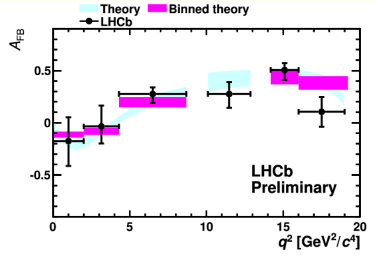
- sensitivity to new physics effects
- complementary to other searches
- probe sectors inaccessible to direct searches
- test quantum structure of the SM at loop level
- constrain parameter spaces of new physics scenarios
- valuable data already available
- promising experimental situation
- consistency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

LHCb and New Physics

Already, a lot of interesting results:

- CP violation
- Rare decays
  - **BR($B_s \to \mu^+\mu^-$)**
  - $B \to K^*\mu^+\mu^-$
  - $B \to K^*\gamma$





In this talk

- Constrained (Conventional) MSSM scenarios
  - implication of $\mathrm{BR}(B_s \to \mu^+\mu^-)$ limit/measurement
  - implication of other rare decays
  - comparison with the direct SUSY limits
- More general MSSM scenarios
  - implications of flavour observables
  - constraints from $\mathrm{BR}(B_s \to \mu^+\mu^-)$
- Beyond SUSY
- Model independent constraints
- Conclusions

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

Effective Hamiltonian:

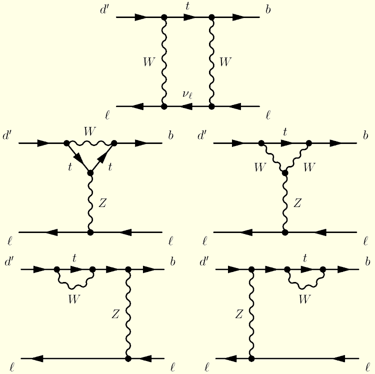
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum C_i(\mu)\mathcal{O}_i(\mu) + \sum C_{Q_i}(\mu) Q_i(\mu)\right)$$

Important operators:

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

$$Q_1 = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\,\ell)$$

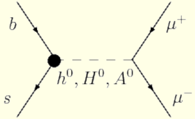
$$Q_2 = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5\ell)$$



$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3} f_{B_s}^2 \tau_{B_s} m_{B_s}^3 |V_{tb}V_{ts}^*|^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}}$$
$$\times \left\{ \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) \left| \left(\frac{m_{B_s}}{m_b + m_s}\right)(C_{Q_1} - C'_{Q_1}) \right|^2 + \left| \left(\frac{m_{B_s}}{m_b + m_s}\right)(C_{Q_2} - C'_{Q_2}) + 2\,(C_{10} - C'_{10})\frac{m_\mu}{m_{B_s}} \right|^2 \right\}$$

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

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



$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{MSSM} \sim \frac{m_b^2 m_\mu^2 \tan^6\beta}{M_A^4}$$

SUSY contributions in BR($B_s \to \mu^+\mu^-$) can lead to an O(100) enhancement over the SM!

Large uncertainty from the decay constant (f_{B_s})!

$\to$ A way out: double ratios of leptonic decays:

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

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

From the form factor and CKM matrix point of view:

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

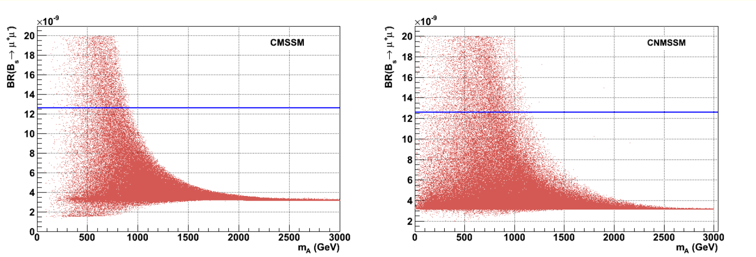
R has no dependence on the decay constants, contrary to each decay taken individually!

Results

LHCb + CMS combined limit: $\mathrm{BR}(B_s \to \mu^+\mu^-) \lesssim 3\times$ SM value

At 95% C.L., including th uncert.: $\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.26 \times 10^{-8}$

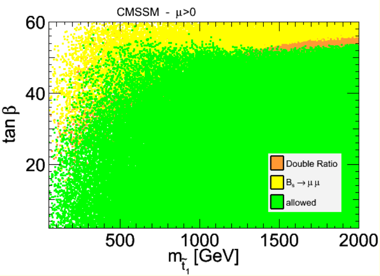
CMSSM CNMSSM



Results

The constraining power in the case of a SM like discovery:

Current limit SM like branching ratio



A.G. Akeroyd, F.M., D. Martinez Santos, arXiv:1108.3018
SuperIso v3.2

Results

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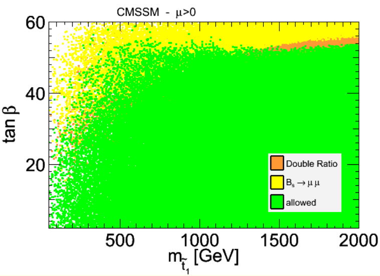
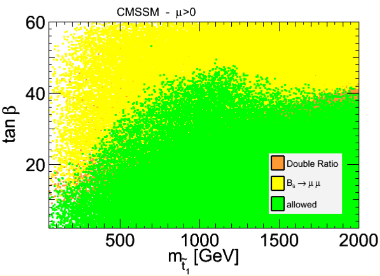
Current limit



SM like branching ratio



A.G. Akeroyd, F.M., D. Martinez Santos, arXiv:1108.3018
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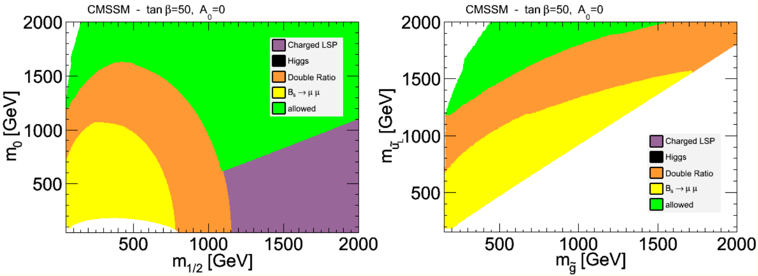

This goes far beyond ATLAS and CMS direct limits!

A.G. Akeroyd, F.M., D. Martinez Santos, arXiv:1108.3018
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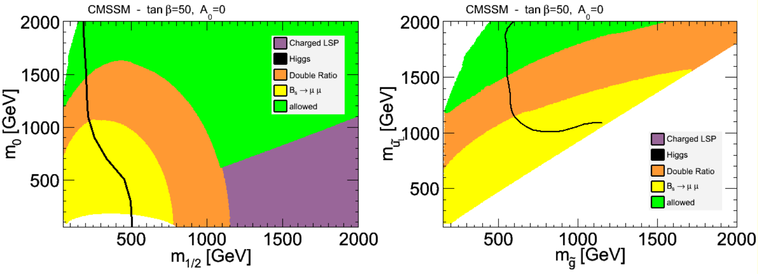
Results

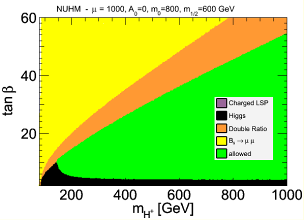


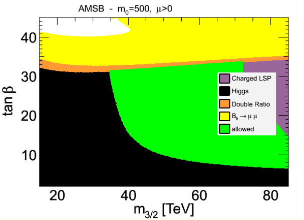
This goes far beyond ATLAS and CMS direct limits!

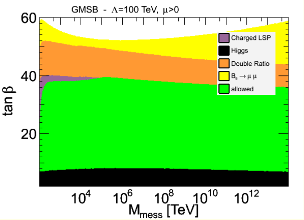
A.G. Akeroyd, F.M., D. Martinez Santos, arXiv:1108.3018
SuperIso v3.2

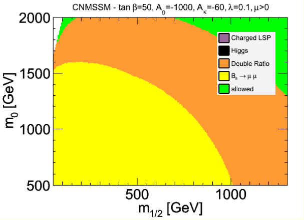
Results

Also very constraining for other constrained MSSM scenarios:







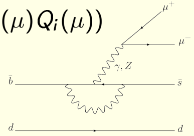


A.G. Akeroyd, F.M., D. Martinez Santos, arXiv:1108.3018

BR($B \to K^* \mu^+ \mu^-$)

Effective Hamiltonian:

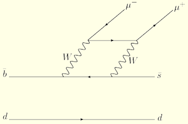
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum C_i(\mu) \mathcal{O}_i(\mu) + \sum C_{Q_i}(\mu) Q_i(\mu)\right)$$



QCDF/SCET $\to$ 7 hadronic form factors

Main operators:

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$$
$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$
$$Q_1 = \frac{e^2}{16\pi^2} (\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\,\ell)$$
$$Q_2 = \frac{e^2}{16\pi^2} (\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\gamma_5 \ell)$$



$\to$ explore full angular analysis, design observables with reduced hadronic uncertainties

In particular, the forward-backward asymmetry is of interest:

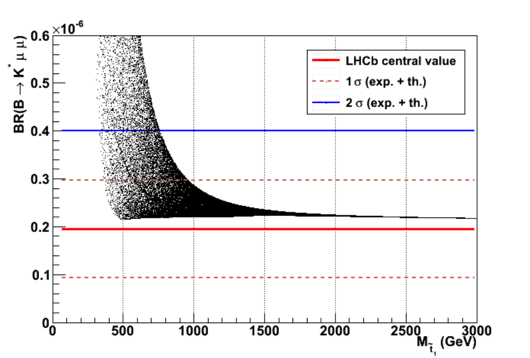
$$A_{FB}(\hat{s}) = \frac{1}{d\Gamma/d\hat{s}} \left[\int_0^1 d(\cos\theta) \frac{d^2\Gamma}{d\hat{s}\, d(\cos\theta)} - \int_{-1}^0 d(\cos\theta) \frac{d^2\Gamma}{d\hat{s}\, d(\cos\theta)} \right]$$

θ: angle between B^0 and μ^+ momenta in the dilepton system center of mass

$\hat{s} = s/M_B^2$, with $s = (p_{\mu^+} + p_{\mu^-})^2$

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

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



For $m_{\tilde{q}} > 750$ GeV, SUSY spread is within the th+exp error

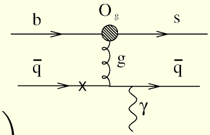
Look at other observables (A_{FB}, F_L,...)

Reduce both theory and experimental errors.

F.M., S. Neshatpour, J. Orloff, work in progress

Isospin asymmetry of $B \to K^*\gamma$

Based on $b \to s\gamma$ transitions.
SUSY contributions from charged Higgs and chargino loops
Isospin asymmetry: very interesting when the interference is destructive



$$\Delta_{0-} \equiv \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) - \Gamma(B^- \to K^{*-}\gamma)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) + \Gamma(B^- \to K^{*-}\gamma)}$$

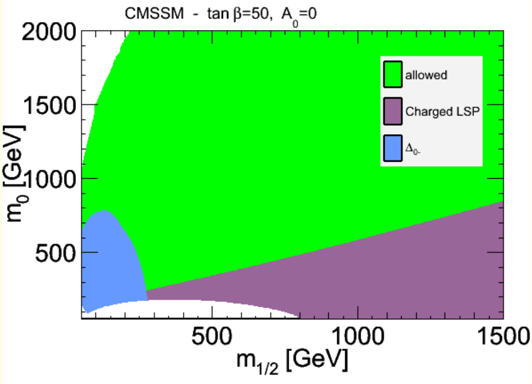
$$\Delta_{0-} = \mathrm{Re}(b_d - b_u)\ ,\ b_q = \frac{12\pi^2 f_B\, Q_q}{m_b\, T_1^{B\to K^*}\, a_7^c}\left(\frac{f_{K^*}^{\perp}}{m_b} K_1 + \frac{f_{K^*}\, m_{K^*}}{6\lambda_B\, m_B} K_2\right)$$

$$a_7^c = C_7 + \frac{\alpha_s(\mu) C_F}{4\pi}\Big(C_1(\mu) G_1(s_p) + C_8(\mu) G_8\Big) + \frac{\alpha_s(\mu_h) C_F}{4\pi}\Big(C_1(\mu_h) H_1(s_p) + C_8(\mu_h) H_8\Big)$$

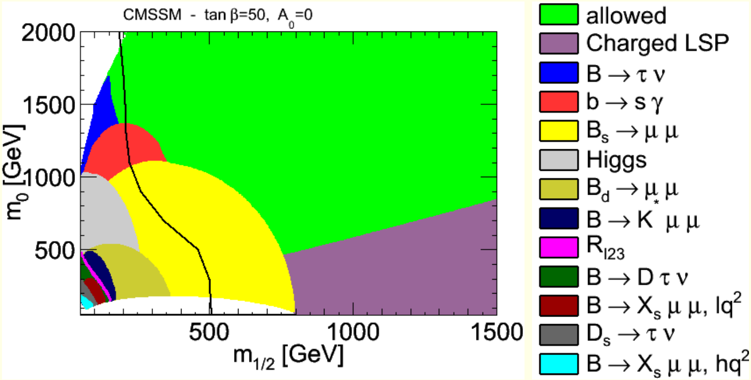
In the Standard Model: $\Delta_{0-} \simeq 8\%$ — Kagan and Neubert, Phys. Lett. B539, 227 (2002)

Experimental value (HFAG): $\Delta_0 = (5.2 \pm 2.6) \times 10^{-2}$

Isospin asymmetry of $B \to K^*\gamma$

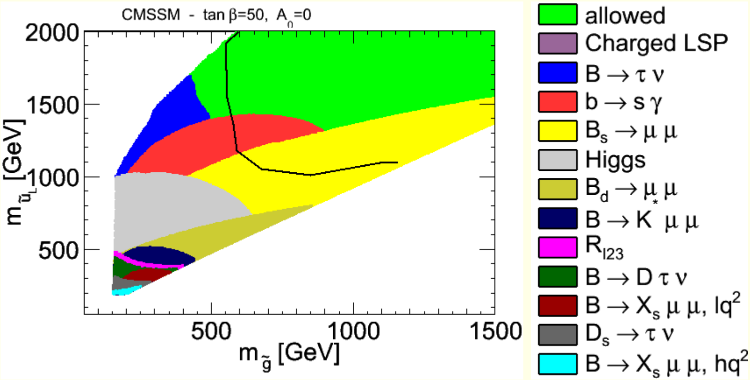


Other rare decays



SuperIso v3.2+

Other rare decays



SuperIso v3.2+

pMSSM

Going beyond constrained scenarios

- CMSSM useful for benchmarking,...
- However the mass patterns could be more complicated
- How do the conclusions change when moving to the MSSM?

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

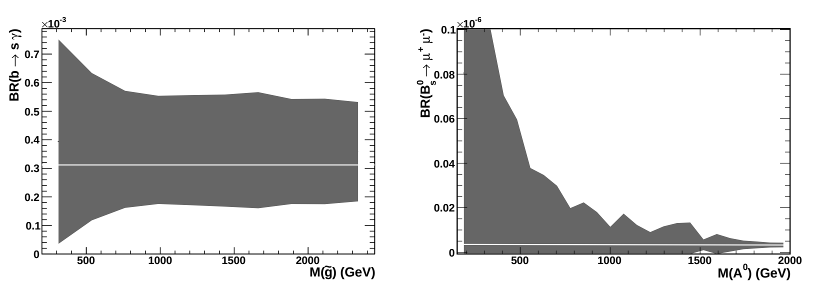
$\rightarrow$ 19 free parameters

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

A. Djouadi, J.-L. Kneur, G. Moultaka, hep-ph/0211331
C.F. Berger et al., JHEP 0902 (2009) 023
S. AbdusSalam et al., Phys. Rev. D81 (2010) 095012
S. Sekmen et al., arXiv:1109.5119
A. Arbey, M. Battaglia, F.M., arXiv:1110.3726

Implication of flavour observables on the pMSSM models

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



A. Arbey, M. Battaglia, F.M., arXiv:1110.3726

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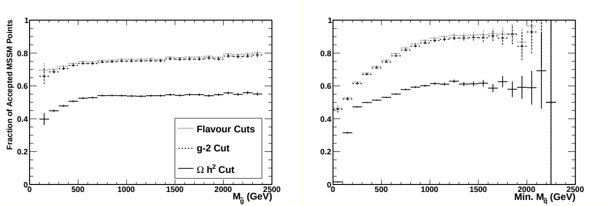
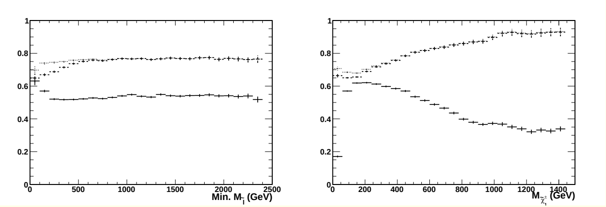


Flavour cuts disfavour masses below ∼500 GeV for the gluino and the lightest scalar quark



A. Arbey, M. Battaglia, F.M., arXiv:1110.3726

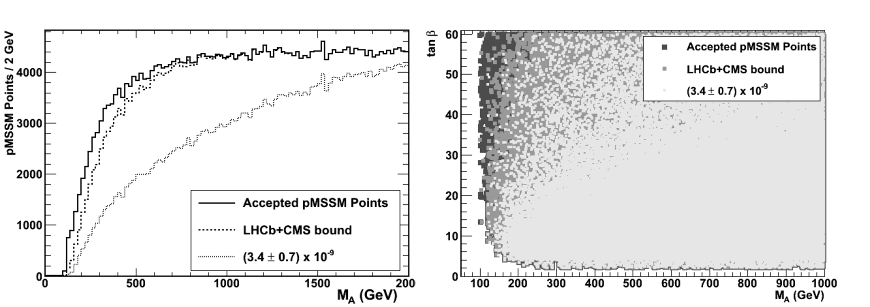
Sensitivity to M_A from BR($B_s \to \mu^+\mu^-$)

Considering 2 scenarios:

- Current 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!

Beyond SUSY

An example: Warped extra dimensions (RS)

- A slice of anti-de Sitter spacetime in five dimensions (AdS_5)
- Fifth dimension ϕ compactified on a S^1/Z^2 orbifold
- Two branes : at orbifold fixed points $\phi = 0$ and $\phi = \pi$
- The warp factor acts as a conformal factor for the fields localized on the brane
  $\rightarrow$ Mass factors get rescaled by this factor
- Solves the hierarchy!

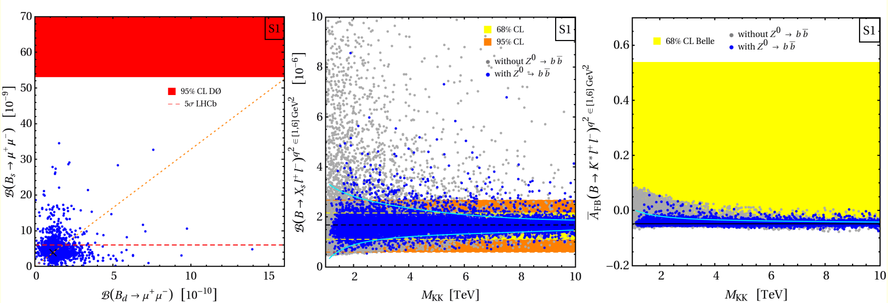
- Only the Higgs field is localized on the TeV brane while the rest of the SM fields are in the bulk
- Localization of fermions close to the TeV brane (overlap with the Higgs)
  $\rightarrow$ large Yukawa couplings
- Localization of fermions close to the Planck brane $\rightarrow$ small Yukawa couplings

Explains the hierarchies in fermion spectrum!
$\rightarrow$ very attractive theory of flavour!

Y. Grossman & M. Neubert, Phys.Lett. B474 (2000) 361; T. Gherghetta & A. Pomarol, Nucl.Phys. B586 (2000) 141
S. Huber & Q. Shafi, Phys.Rev. D63 (2001) 045010; G. Burdman, Phys.Lett. B590 (2004) 86
K. Agashe et al., Phys.Rev.Lett. 93 (2004) 201804; M. Bauer et al., JHEP 1009 (2010) 017

Warped extra dimensions (RS): benchmark scenario S1

Modified Wilson coefficients



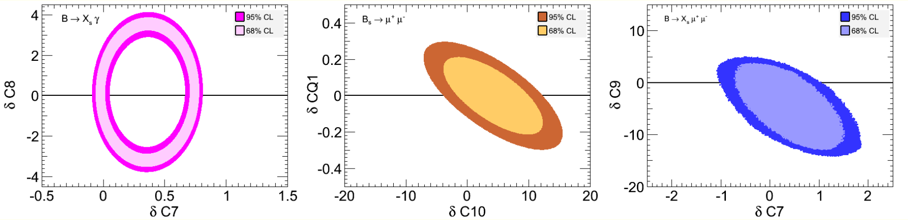
Horizontal lines: SM values
Horizontal coloured bands: excluded ($B_s \to \mu^+\mu^-$) / favoured (other decays) regions
Gray points: inconsistent with measured $Z^0 \to b\bar{b}$ at 99% C.L.
Blue points: consistent with measured $Z^0 \to b\bar{b}$ at 99% C.L.

M. Bauer, S. Casagrande, U. Haisch, M. Neubert, JHEP 1009 (2010) 017

Constraints on Wilson Coefficients

Use the existing limits/measurements to find the allowed intervals for the Wilson coefficients

Make predictions for other observables!



Guideline for model building!

T. Hurth, F.M., work in progress

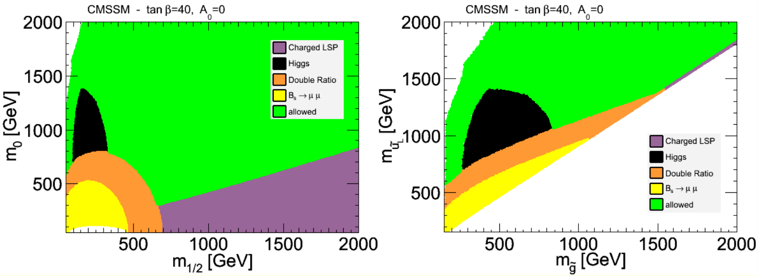
Conclusion

- Flavour physics plays a very important role in constraining BSM scenarios
- Brings valuable information when combined with the direct search data
- The constrained SUSY scenarios are highly constrained
- General MSSM: A lot of viable model points survive, but combining with other sectors, one can squeeze the parameter space
- Room for a lot of work in non-SUSY and/or model independent analyses

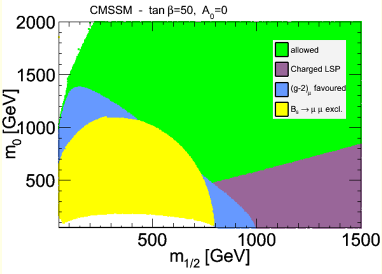
Backup

Backup

Constrained MSSM

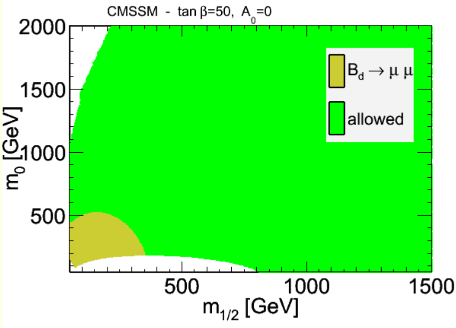


Constrained MSSM



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

- Process similar to $B_s \to \mu^+\mu^-$
- CKM suppressed
- SM prediction: BR($B_d \to \mu^+\mu^-$) $= (1.1 \pm 0.1) \times 10^{-10}$
- LHCb limit: BR($B_d \to \mu^+\mu^-$) $< 5.1 \times 10^{-9}$ at 95% C.L.



pMSSM scans

Flat scans over the pMSSM 19 parameters.

- Spectrum generation (SoftSusy)
- Low energy observables (**SuperIso**)
- Dark matter (**SuperIso Relic**, Micromegas)
- SUSY and Higgs mass limits (SuperIso, HiggsBounds)
- Higgs and SUSY decays (HDECAY, Higlu, FeynHiggs, SDECAY)
- Event generation and cross sections (PYTHIA, Prospino)
- Detector simulation (Delphes)

$2.16 \times 10^{-4} < \mathrm{BR}(B \to X_s\gamma) < 4.93 \times 10^{-4}$
$\mathrm{BR}(B_s \to \mu^+\mu^-) < 1.26 \times 10^{-8}$
$0.56 < \mathrm{R}(B \to \tau\nu) < 2.70$
$4.7 \times 10^{-2} < \mathrm{BR}(D_s \to \tau\nu) < 6.1 \times 10^{-2}$
$2.9 \times 10^{-3} < \mathrm{BR}(B \to D^0\tau\nu) < 14.2 \times 10^{-3}$
$0.985 < \mathrm{R}_{\mu 23}(K \to \mu\nu) < 1.013$
$-2.4 \times 10^{-9} < \delta a_\mu < 4.5 \times 10^{-9}$
$10^{-4} < \Omega_\chi h^2 < 0.135$
+ sparticle mass upper bounds
+ Higgs search limits

pMSSM scans

Parameter	Range
$\tan\beta$	[1, 60]
M_A	[50, 2000]
M_1	[-2500, 2500]
M_2	[-2500, 2500]
M_3	[50, 2500]
$A_d = A_s = A_b$	[-2000, 2000]
$A_u = A_c = A_t$	[-2000, 2000]
$A_e = A_\mu = A_\tau$	[-2000, 2000]
μ	[-1000, 2000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[50, 2500]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[50, 2500]
$M_{\tilde{\tau}_L}$	[50, 2500]
$M_{\tilde{\tau}_R}$	[50, 2500]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[50, 2500]
$M_{\tilde{q}_{3L}}$	[50, 2500]
$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	[50, 2500]
$M_{\tilde{t}_R}$	[50, 2500]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[50, 2500]
$M_{\tilde{b}_R}$	[50, 2500]

Selection	pMSSM points	Selection Efficiency	Cumulative Efficiency
Generated Points	24.57M	1	1
Valid Spectra	9.41M	0.383	0.383
$\tilde{\chi}_1^0$ LSP and Mass Limits	2.62M	0.278	0.107
Higgs Limits	1.81M	0.691	0.074
Flavour and $g_\mu - 2$	1.34M	0.743	0.055
$\Omega_\chi h^2$	897k	0.668	0.037
Successfull Simulation	835k	0.931	0.034