

Interplay between direct and indirect searches

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Implications of LHCb measurements and future prospects

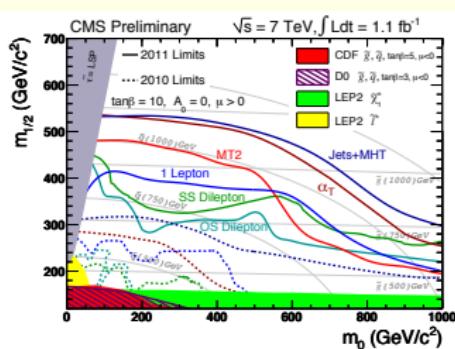
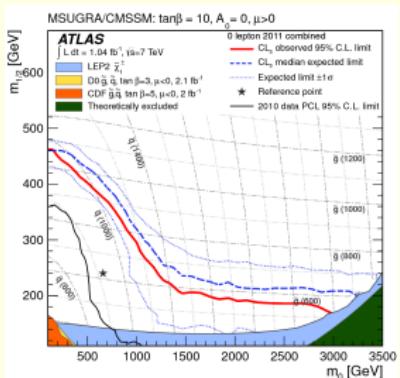
CERN, 10-11 November 2011



Direct searches for new particles

ATLAS & CMS

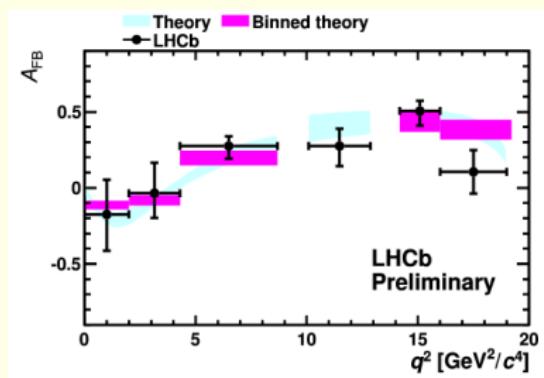
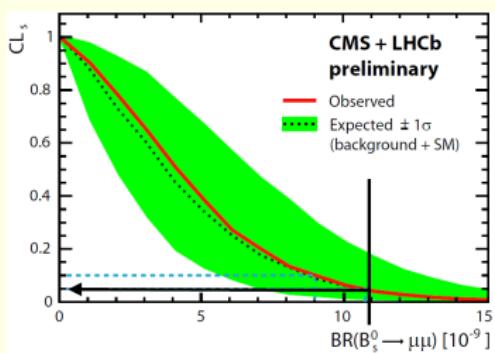
- Interesting results and limits from direct searches by both ATLAS and CMS
- A lot of effort on Higgs searches
- A lot of effort on SUSY searches
 - Most of the results shown in terms of constrained SUSY scenarios
- No signal yet...



Indirect constraints from flavour physics

LHCb

- $B_s \rightarrow \mu^+ \mu^-$
- $B \rightarrow K^* \mu^+ \mu^-$
- CP violation (see yesterday's talks)



Interplay between direct and indirect searches

How the combination of information from both sectors can help us to pin down the underlying NP scenario?

Take supersymmetry as our NP scenario for this talk.

- Direct searches for SUSY particles: the limits on the masses are being pushed higher and higher.
- This is not enough!
- Interplay can play a crucial role

Also interesting non-LHC data on dark matter



$\text{BR}(B_s \rightarrow \mu^+ \mu^-)$

Effective Hamiltonian:

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

Important operators:

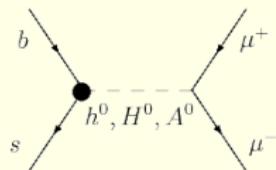
$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5\ell)$$

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

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

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

SUSY contributions in $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$ can lead to an O(100) enhancement over the SM!



$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)_{\text{MSSM}} \sim \frac{m_b^2 m_\mu^2 \tan^6 \beta}{M_A^4}$$

Double ratios of leptonic decays

For example:

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

From the form factor and CKM matrix point of view:

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

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

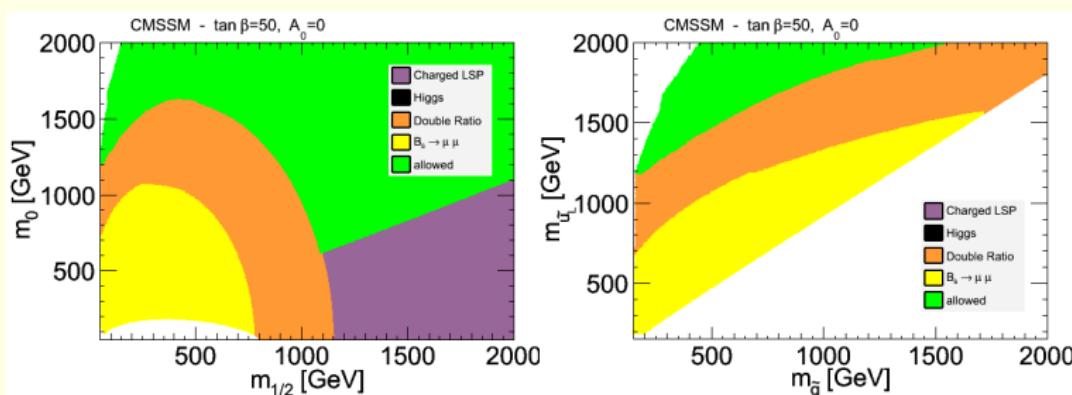
B. Grinstein, Phys. Rev. Lett. 71 (1993)

A. G. Akeroyd, FM, JHEP 1010 (2010)

Constraints in CMSSM

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

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



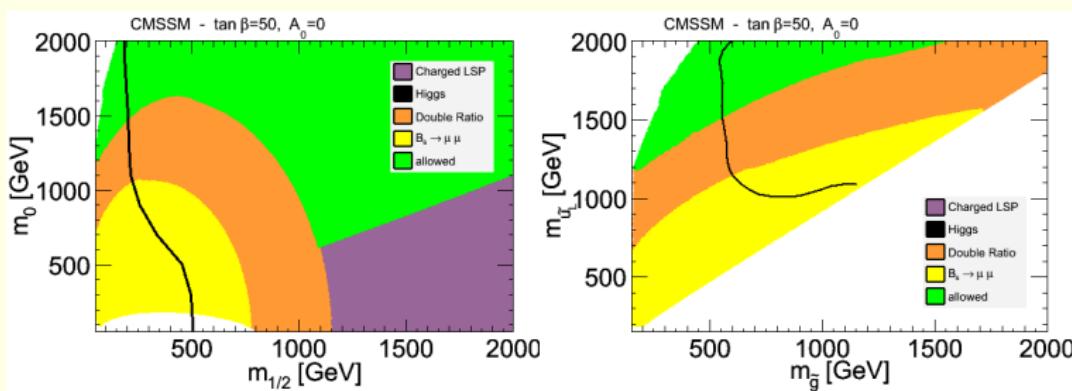
This goes far beyond ATLAS and CMS direct limits!

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

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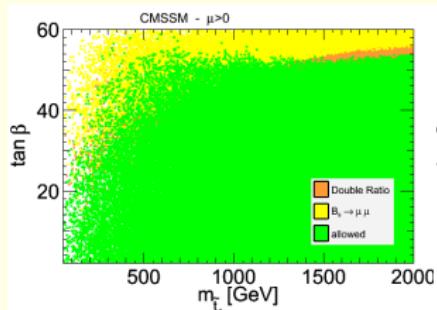


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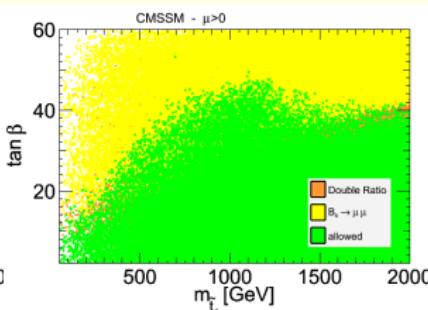
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Other constrained scenarios

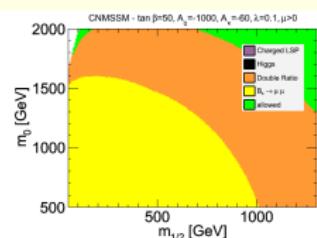
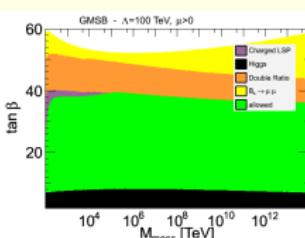
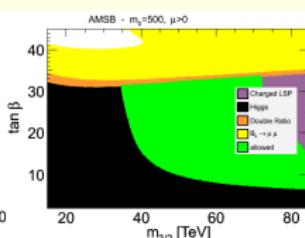
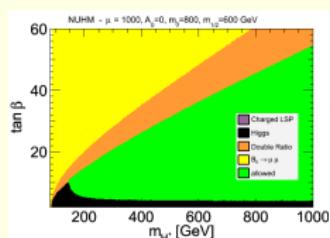
Current limit



SM like branching ratio



Also very constraining for other constrained MSSM scenarios:



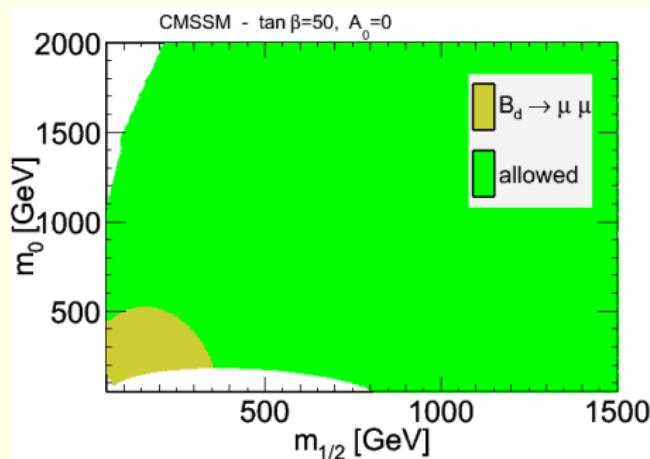
$\text{BR}(B_d \rightarrow \mu^+ \mu^-)$

Process similar to $B_s \rightarrow \mu^+ \mu^-$

CKM suppressed

SM prediction: $\text{BR}(B_d \rightarrow \mu^+ \mu^-) = (1.1 \pm 0.1) \times 10^{-10}$

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



$$\text{BR}(B \rightarrow K^* \mu^+ \mu^-)$$

Effective Hamiltonian:

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

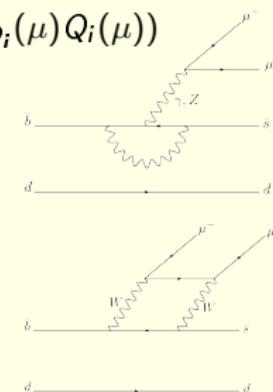
Main operators:

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

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

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

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



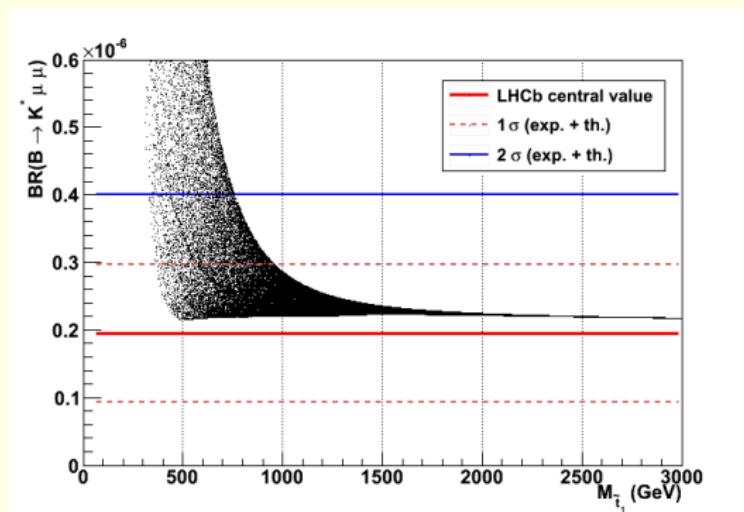
Various observables, angular distributions, ...

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

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

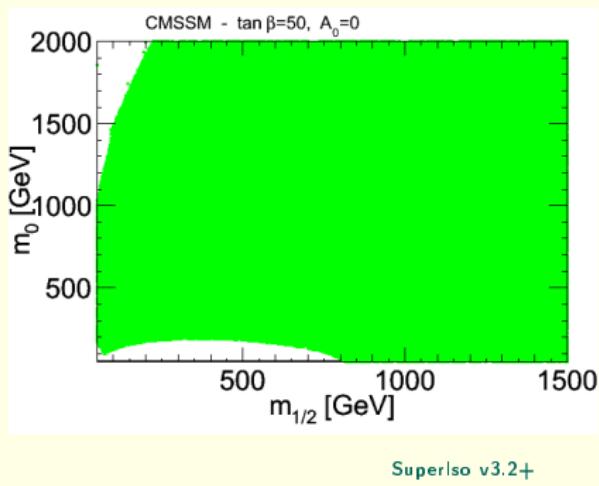
$B \rightarrow K^* \mu^+ \mu^-$
 $\text{BR}(B \rightarrow K^* \mu^+ \mu^-)$ in the low q^2 region:


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.

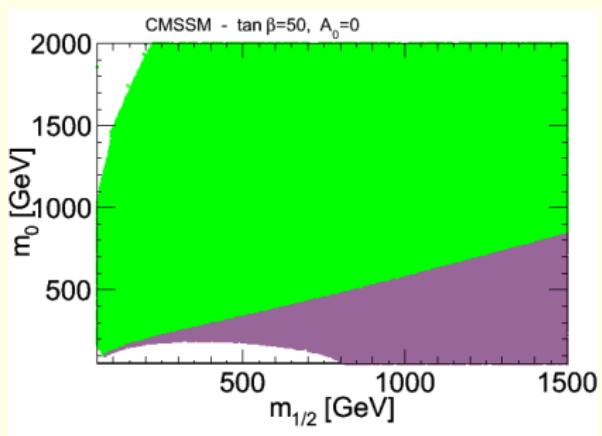
Other rare decays



CMSSM parameter space

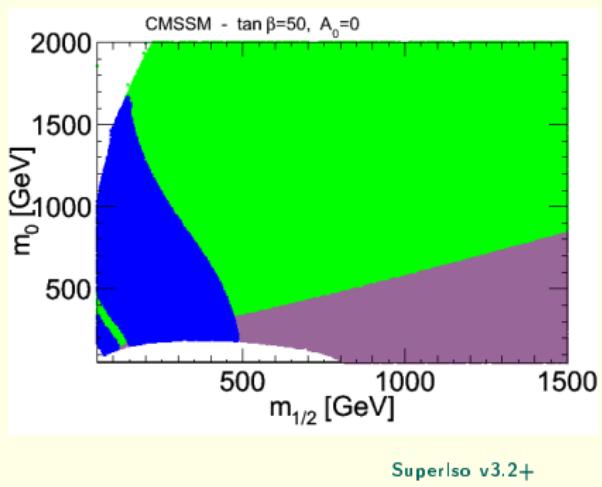
$\tan \beta = 50, A_0 = 0$

Other rare decays



Stable charged LSP incompatible with cosmology

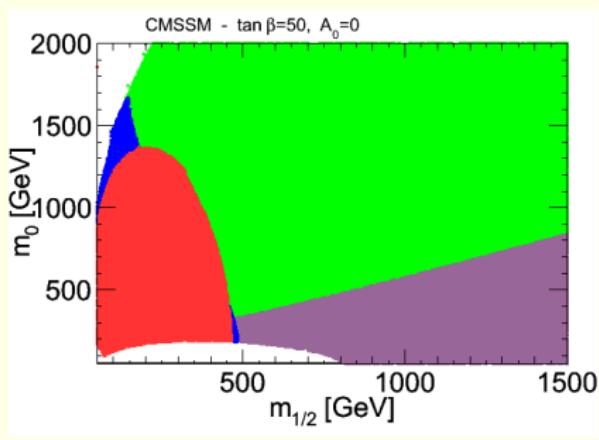
Other rare decays



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

HFAG 2011:
 $\mathcal{B}(B \rightarrow \tau \nu) = (1.64 \pm 0.34) \times 10^{-4}$

Other rare decays



$$B \rightarrow X_s \gamma$$

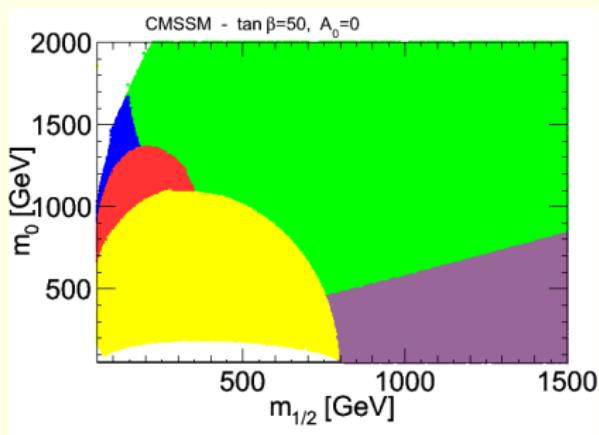
NNLO calculation

Misiak et al., PRL 98, 022002

Experimental value – HFAG 2011:

$$\mathcal{B}[\bar{B} \rightarrow X_s \gamma] = (3.55 \pm 0.25) \times 10^{-4}$$

Other rare decays

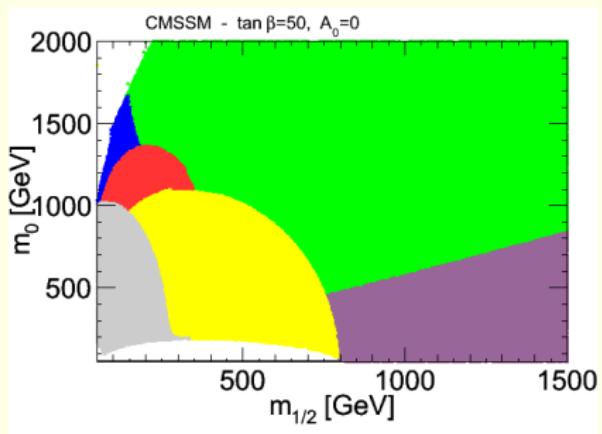


$$B_s \rightarrow \mu^+ \mu^-$$

LHCb + CMS combination:

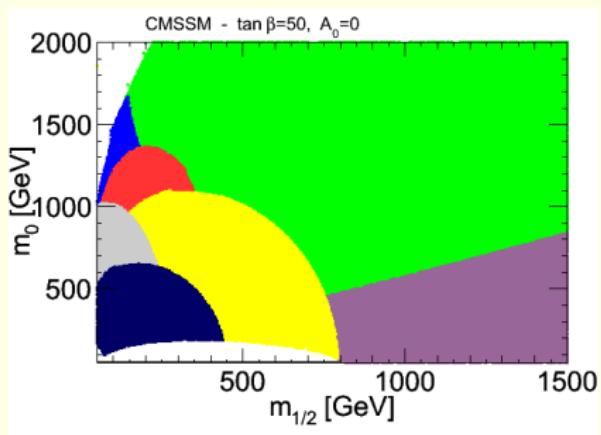
$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) < 1.1 \times 10^{-8} \text{ at 95% C.L.}$$

Other rare decays



Higgs direct searches

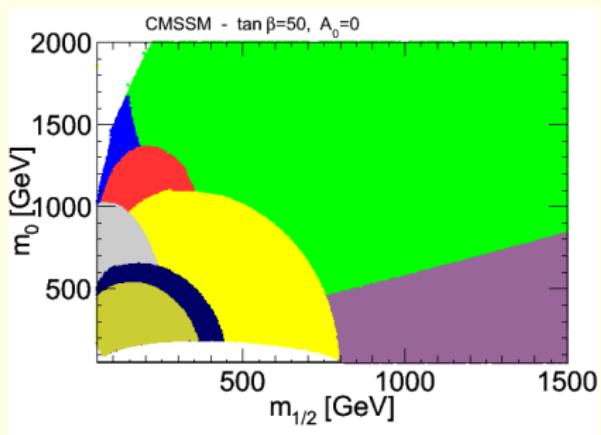
Other rare decays



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

In the region $1 < q^2 < 6$ GeV 2 (LHCb):
 $\mathcal{B}(B \rightarrow K^* \mu^+ \mu^-) = (1.95 \pm 0.31) \times 10^{-7}$

Other rare decays

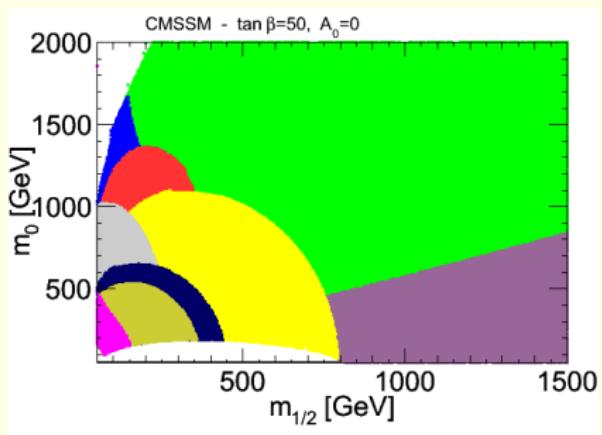


$$B_d \rightarrow \mu^+ \mu^-$$

LHCb limit:

$$\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) < 5.1 \times 10^{-9} \text{ at 95% C.L.}$$

Other rare decays



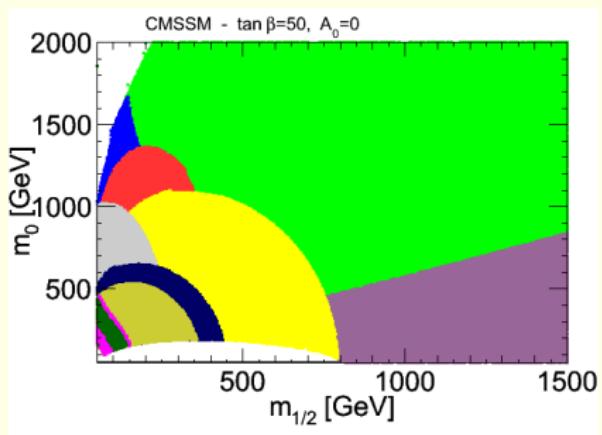
$$K \rightarrow \mu\nu$$

$$R_{\ell 23} = \left| \frac{V_{us}(K_{\ell 2})}{V_{us}(K_{\ell 3})} \times \frac{V_{ud}(0^+ \rightarrow 0^+)}{V_{ud}(\pi \ell 2)} \right| = \\ \left| 1 - \frac{m_{K^+}^2}{M_{H^+}^2} \left(1 - \frac{m_d}{m_s} \right) \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta} \right|$$

Combined experimental and SM constraint:

$$R_{\ell 23}^{\text{exp/SM}} = 1.004 \pm 0.014$$

Other rare decays

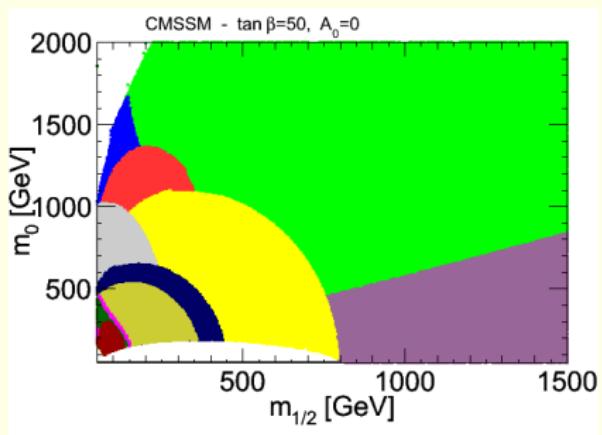


$$\frac{d\Gamma(B \rightarrow D \ell \bar{\nu})}{dw} = \frac{G_F^2 |V_{cb}|^2 m_B^5}{192\pi^3} \rho_V(w) \times \left[1 - \frac{m_\ell^2}{m_B^2} \left| 1 - \frac{t(w)}{(m_b - m_c)} \frac{m_b}{m_{H^+}^2} \frac{\tan^2 \beta}{1 + \epsilon_0 \tan \beta} \right|^2 \rho_S(w) \right]$$

PDG 2011:

$$\frac{\mathcal{B}(B^- \rightarrow D^0 \tau^- \bar{\nu})}{\mathcal{B}(B^- \rightarrow D^0 e^- \bar{\nu})} = 0.416 \pm 0.117 \pm 0.052$$

Other rare decays

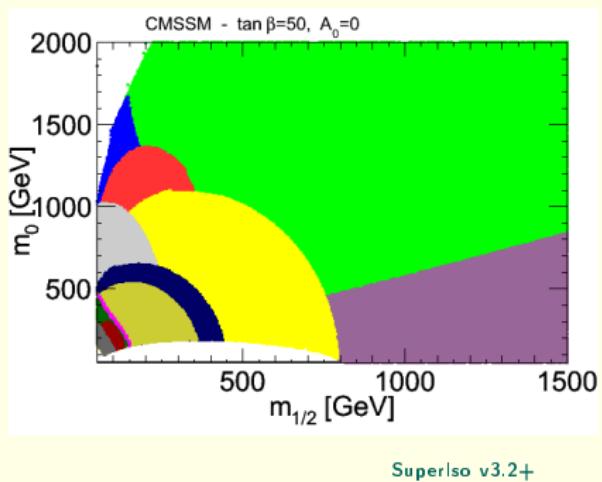


$$B \rightarrow X_s \mu^+ \mu^-, \text{ high } q^2$$

Experimental value:

$$\mathcal{B}(B \rightarrow X_s \mu^+ \mu^-) = (4.18 \pm 1.35) \times 10^{-7}$$

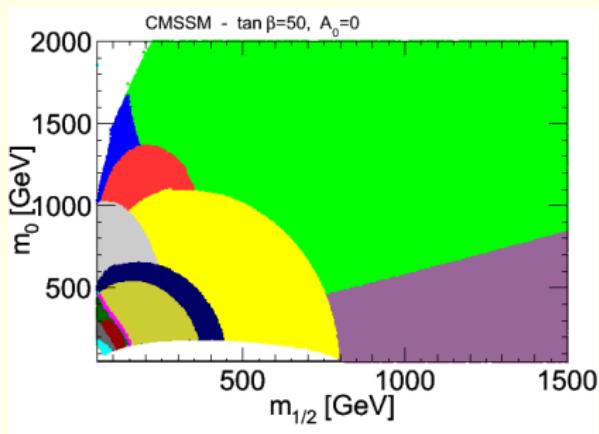
Other rare decays



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

HFAG 2011:
 $\mathcal{B}(D_s \rightarrow \tau \nu) = (5.38 \pm 0.32) \times 10^{-2}$

Other rare decays

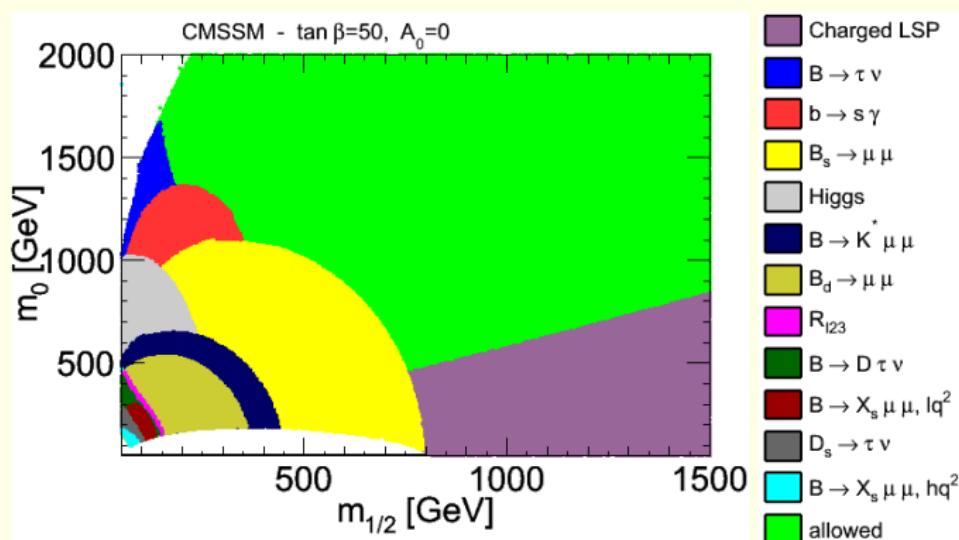


$$B \rightarrow X_s \mu^+ \mu^-, \text{ low } q^2$$

Experimental value:

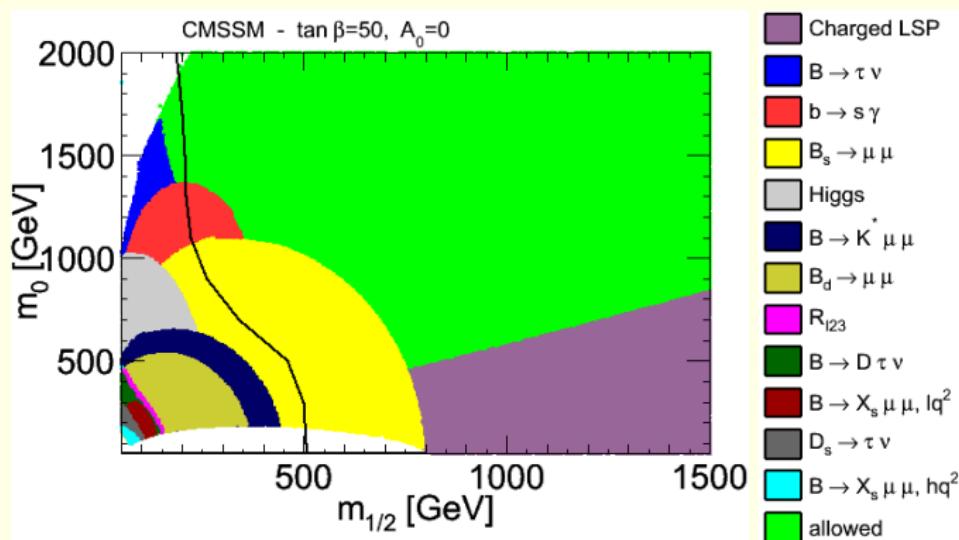
$$\mathcal{B}(B \rightarrow X_s \mu^+ \mu^-) = (1.60 \pm 0.68) \times 10^{-6}$$

Other rare decays



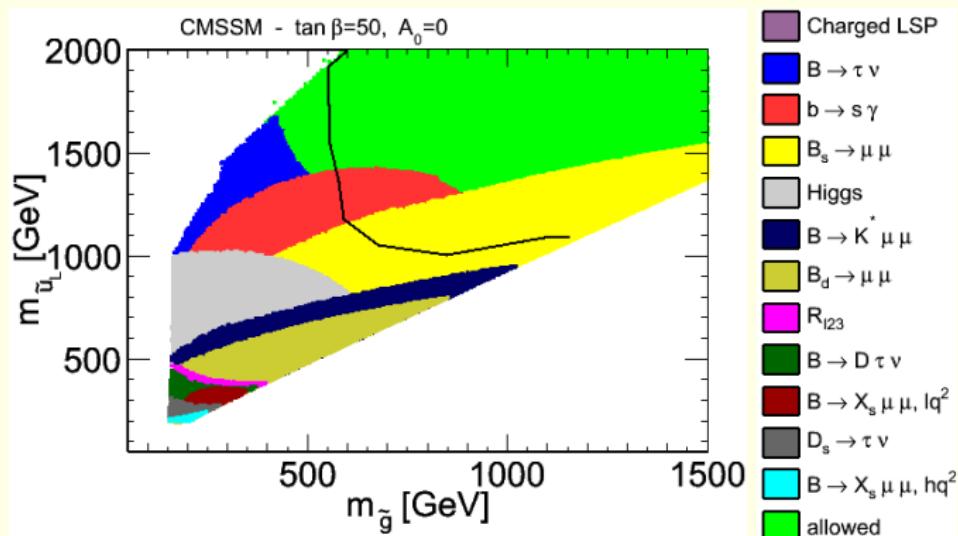
SuperIso v3.2+

Other rare decays



SuperIso v3.2+

Other rare decays



SuperIso v3.2+

pMSSM

Going beyond constrained scenarios

- CMSSM useful benchmarking, model discrimination,...
- 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](#)

Interplay between low energy observables, relic density, direct dark matter searches and the LHC

Constraints on the pMSSM

Play the same game in a larger space → e.g. constraints on SUSY through squark and gluino searches

Viable solutions for masses well above sensitivity of 7 TeV run

Other possibilities?

Constraining the pMSSM through the Higgs sector

→ interplay between flavour, dark matter and direct searches in the Higgs sector

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

A. Arbey, M. Battaglia, F.M., to appear

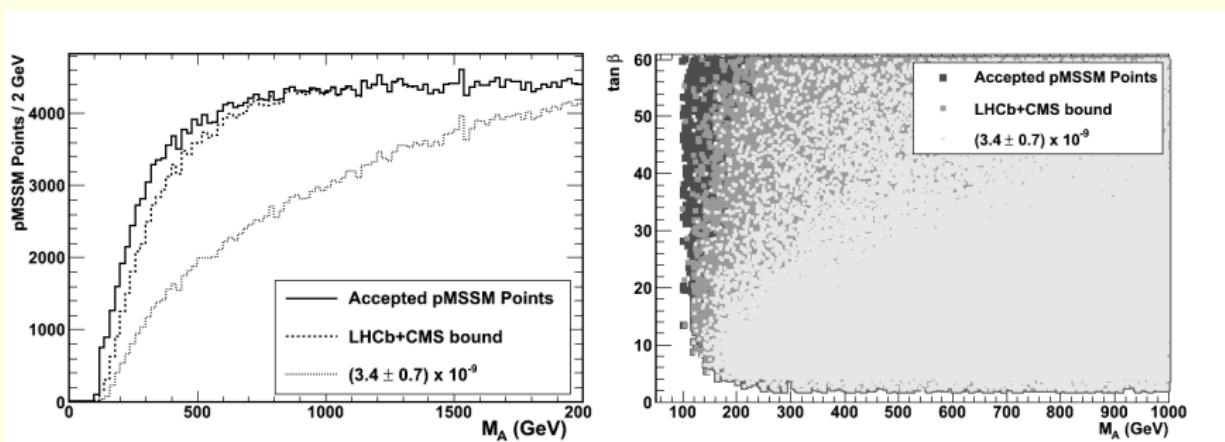
Sensitivity to M_A from $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$

Considering 2 scenarios:

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

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

- SM like branching ratio with estimated 20% total uncertainty

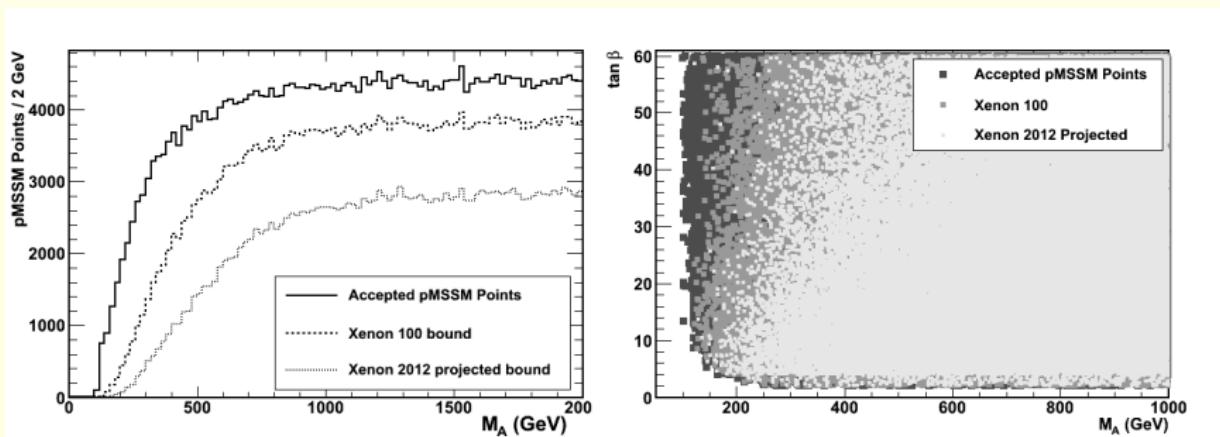


Light M_A strongly constrained!

Dark matter direct detection

Considering 2 scenarios:

- Current Xenon 100 limit
- Projected 2012 90% C.L. upper limit



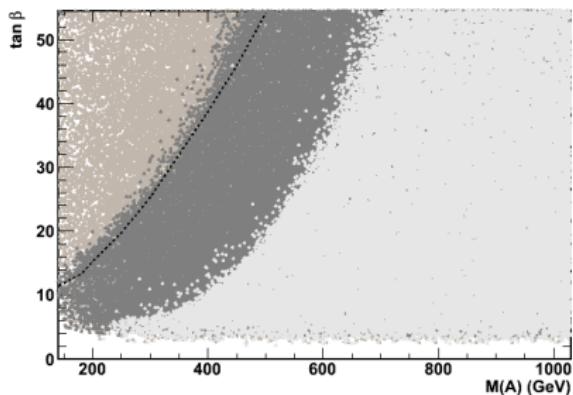
Again light M_A strongly constrained!

Higgs searches

Direct searches for $A \rightarrow \tau\tau$

see CMS-PAS-HIG-11-009

Allowed region of $(M_A, \tan \beta)$ from full pMSSM scans for 1.1 and 15 fb^{-1} compared to published CMS expected limit



Low M_A region below 350 GeV can be explored and excluded if no signal except a narrow strip around $\tan \beta = 5$.

Conclusion

- Interplay between direct and indirect searches is very important and will play a crucial role in the coming year
- The constrained SUSY scenarios are highly constrained
- General MSSM: A lot of viable model points survive, but combining with flavour and dark matter sector information, one can squeeze the parameter space
- The study in SUSY is very illustrative, but can be repeated for other NP models.
- Another approach: Model independent constraints on Wilson coefficients (see next talk)

Backup

Backup

Constrained MSSM

