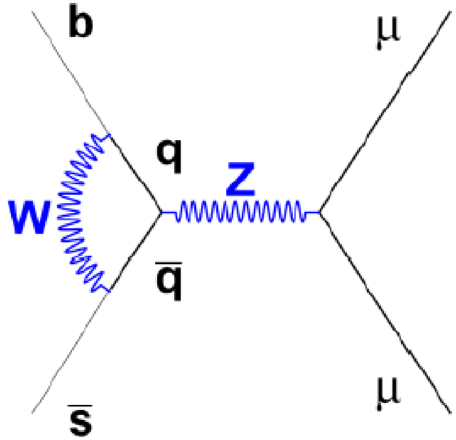
Implications of $B_s \to \mu\mu$ upper limits

Diego Martinez Santos (CERN)

Introduction

- $B_s \to \mu\mu$ is a FCNC, accessible for LHCb, CMS
    - For details on the experimental analysis, see X.Cid in the flavor section
- CMS & LHCb released a combined result at EPS saying $BR(B_s \to \mu\mu) < \sim 3x$ SM.
- This talk: implications of such a measurement
    - $B_s \to \mu\mu$ alone
    - $B_s \to \mu\mu$ on top of other observables



Disclaimer: I'm an experimentalist. Sorry if some of this is inaccurate / wrong!

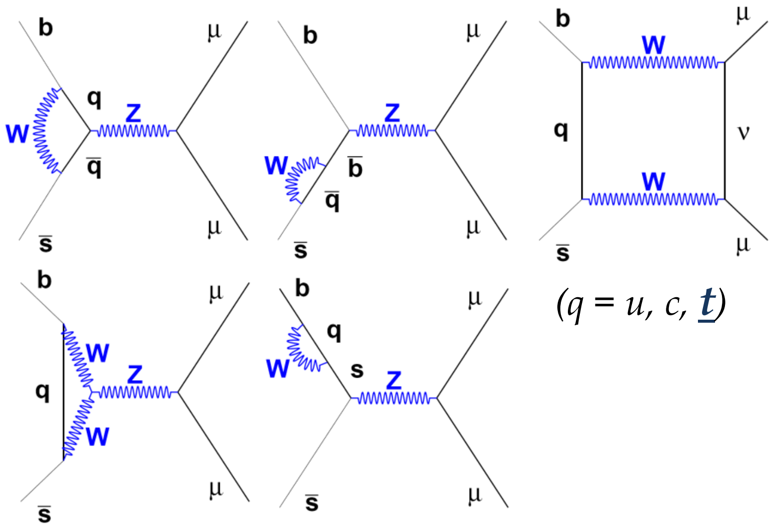
Decay Physics (SM)

Model ~independent expression:

$$BR(B_q \to \mu^+\mu^-) = \frac{G_F^2 \alpha^2}{64\pi^3} |V_{tb}^* V_{tq}|^2 \tau_{Bq} M_{Bq}^3 f_{Bq}^2 \sqrt{1 - \frac{4m_\mu^2}{M_{Bq}^2}} \times$$

$$\times \left\{ M_{Bq}^2 \left(1 - \frac{4m_\mu^2}{M_{Bq}^2}\right) |C_S|^2 + \left[M_{Bq} C_P + \frac{2m_\mu}{M_{Bq}} C_{10} \right]^2 \right\}$$

SM *SM*



(q = u, c, t)

$C_{S,P} \to$ scalar and pseudo scalar are negligible in SM

C_{10} gives the only relevant contribution

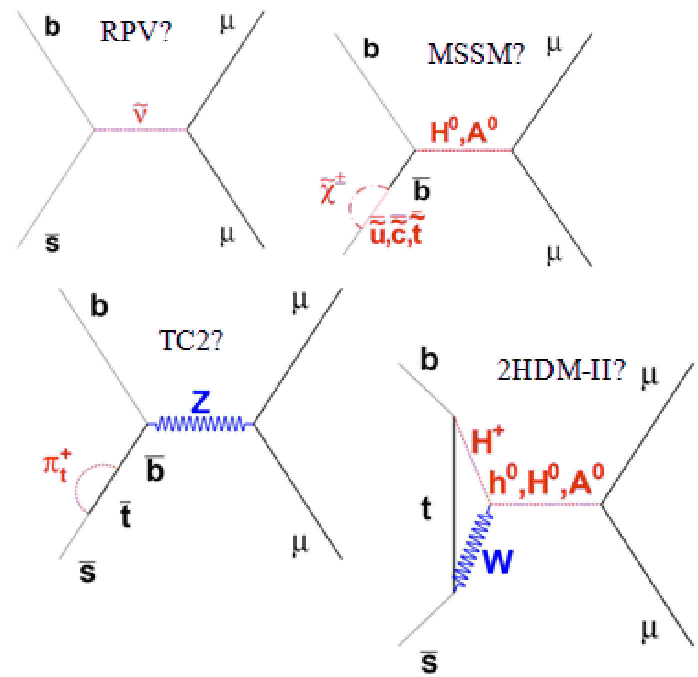
This decay is very suppressed in SM: **$BR(B_s \to \mu\mu) = (3.5 \pm 0.3)\times10^{-9}$**

New Physics effects

NP

- More than one Higgs → contributions to $\mathbf{C_{S,P}}$
  - 2HDM-II : BR proportional to $\tan^4\beta$
  - SUSY (MSSM): above + extra $\tan^6\beta$ +…

- RPV SUSY: tree level diagrams
- Technicolor (TC2), Little Higgs (LHT) … modify $\mathbf{C_{10}}$.



→ ***Whatever the actual value is, it will have an impact on NP searches***

(For a collection of references of Bsmm in different models see CERN-THESIS-2010-068)

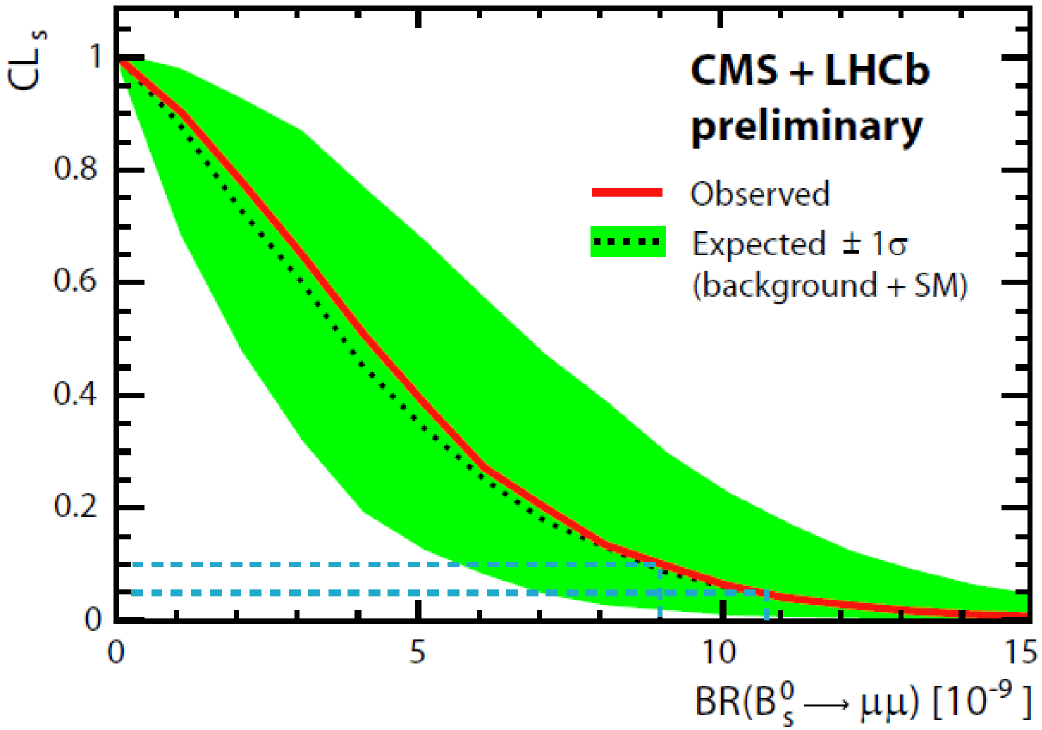
New Physics effects

Scenario	would point to …
$BR(B_s \to \mu\mu) >> SM$	Big enhancement from NP in scalar sector, SUSY high tanβ
$BR(B_s \to \mu\mu) \neq SM$	SUSY (C_S, C_P) , ED's, LHT, TC2 (C_{10})…
$BR(B_s \to \mu\mu) \sim SM$	Anything (→ rule out regions of parameter space that predict sizable departures from SM. Obviously)
$BR(B_s \to \mu\mu) << SM$	NP in scalar sector, but full MSSM ruled out. NMSSM (Higgs singlet) good candidate
$BR(B_s \to \mu\mu) / BR(B_d \to \mu\mu) \neq SM$	CMFV ruled out. New FCNC sources fully independent of CKM matrix (RPV SUSY, ED's etc…)

LHCb & CMS combination (EPS 2011)

LHCb-CONF-2011-047, CMS PAS BPH-11-019

CMS limit (1.9×10^{-8} @ 95 % CL) very competitive with LHCb
Results combined using LHCb's fd/fs, and considered 100% correlated between the 2 experiments



$BR(B_s \to \mu\mu) < 0.9 \times 10^{-8}$ @ 90% CL
$BR(B_s \to \mu\mu) < 1.1 \times 10^{-8}$ @ 95% CL

(rem. SM ~ 3.5×10^{-9})

The observed distribution of events agrees very well with bkg +SM
CL_b ~92 % (→ Probability of bkg-anlone is ~8%. Not enough to claim discovery, though)

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MSSM

Higgs scalar Fields Hu, Hd

1. Gauge part = SM:

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y \longrightarrow SU(3)_C \times U(1)_{EM}$$

2. Supersymmetry: SM particles ⇔ "superpartners" (particle + superpartner ➔ superfield):
 SM fermion ⇔ SUSY boson (sfermions: selectron, squark …)
 SM boson / higgses ⇔ SUSY fermion (-inos: gluino, photino …)

 → Broken (superpartners not been seen yet → heavier): All renormalizable SUSY breaking terms are considered (in principle) ➔ A total of 124 free parameters

3. **R – parity** (= $(-1)^{3(B-L)+2S}$) conservation (consequence of B-L invariance)
 SM particles: R = +1; superpartners : R = -1.
 ➔Superpartners produced/annihilated in pairs ➔ Exists **one stable SUSY particle**: LSP (Lightest SUSY Particle), candidate for Dark Matter

MSSM is usually simplified by imposing some conditions, usually related to the way in which SUSY is broken. mSUGRA, CMSSM, NUHM (I and II), AMSB, GMSB

NMSSM

Similar to MSSM, but the interaction in the .. term

$$\mu \hat{H}_u \hat{H}_d \quad \longrightarrow \quad \lambda \hat{S} \hat{H}_u \hat{H}_d$$

happens through **a Higgs singlet**

(and then you have few terms in the lagrangian related to this higgs singlet)

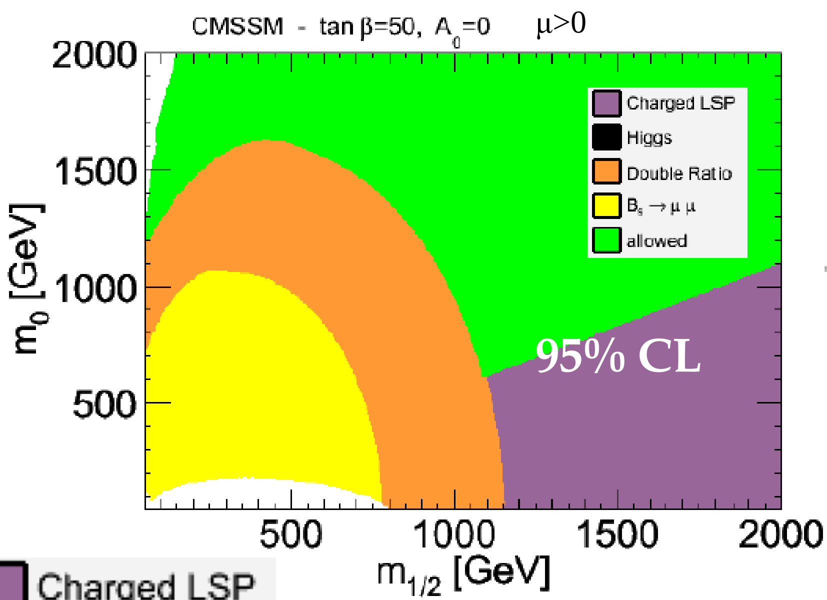
The decay $B_s \to \mu\mu$: updated SUSY constraints and prospects [1108.3018] (submitted to JHEP)

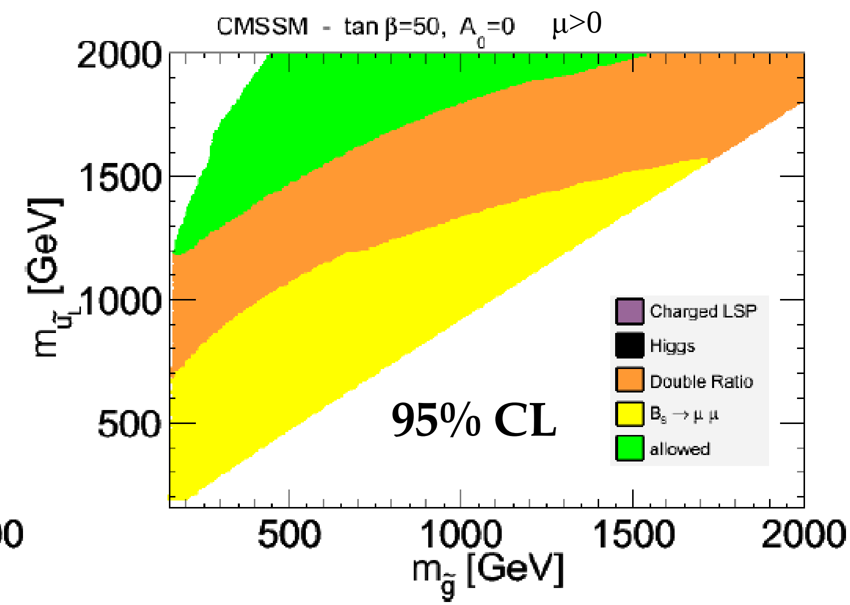
F. Mahmoudi, A.G. Akeroyd, D. Martinez Santos

[Exclusions plots made with SuperIso v3.2]

CMSSM

$$\{m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sgn}(\mu)\}$$



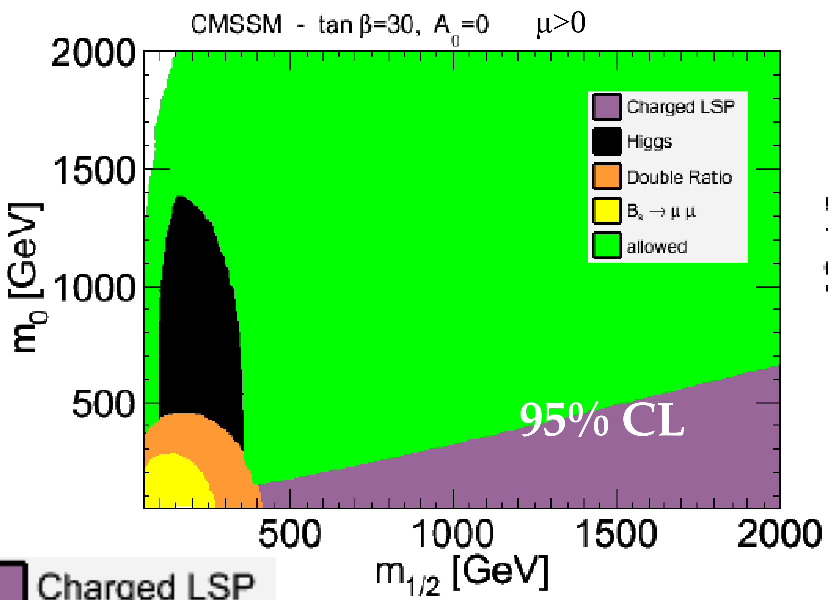


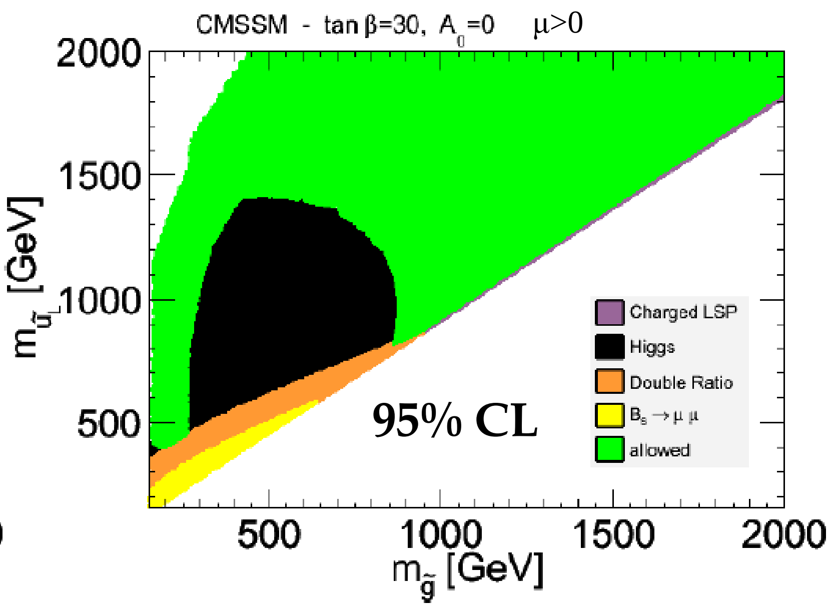
high tanβ

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

CMSSM

$$\{m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sgn}(\mu)\}$$



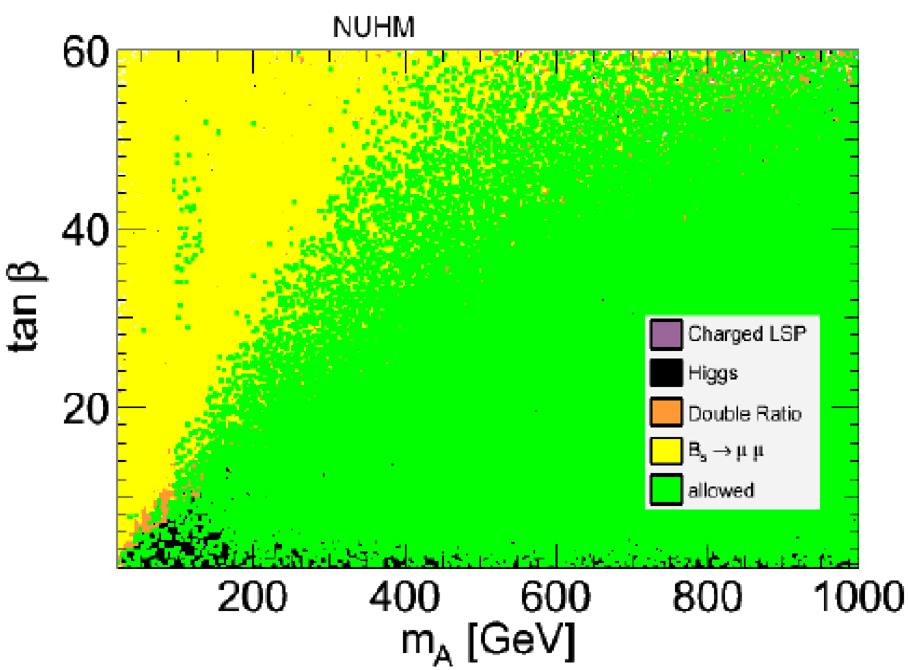


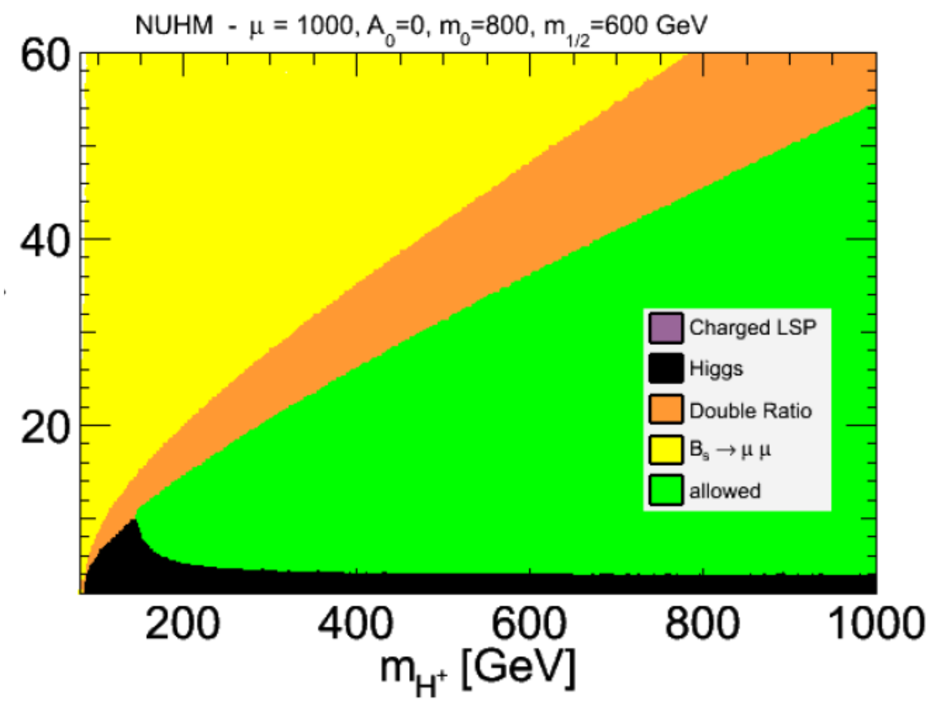
moderate tanβ

$$R \equiv \frac{\eta}{\eta_{\rm SM}} \qquad \eta \equiv \left(\frac{{\rm BR}(B_s \to \mu^+\mu^-)}{{\rm BR}(B_u \to \tau\nu)}\right) \Big/ \left(\frac{{\rm BR}(D_s \to \tau\nu)}{{\rm BR}(D \to \mu\nu)}\right)$$

NUHM-II

CMSSM + { |μ| , m_A}

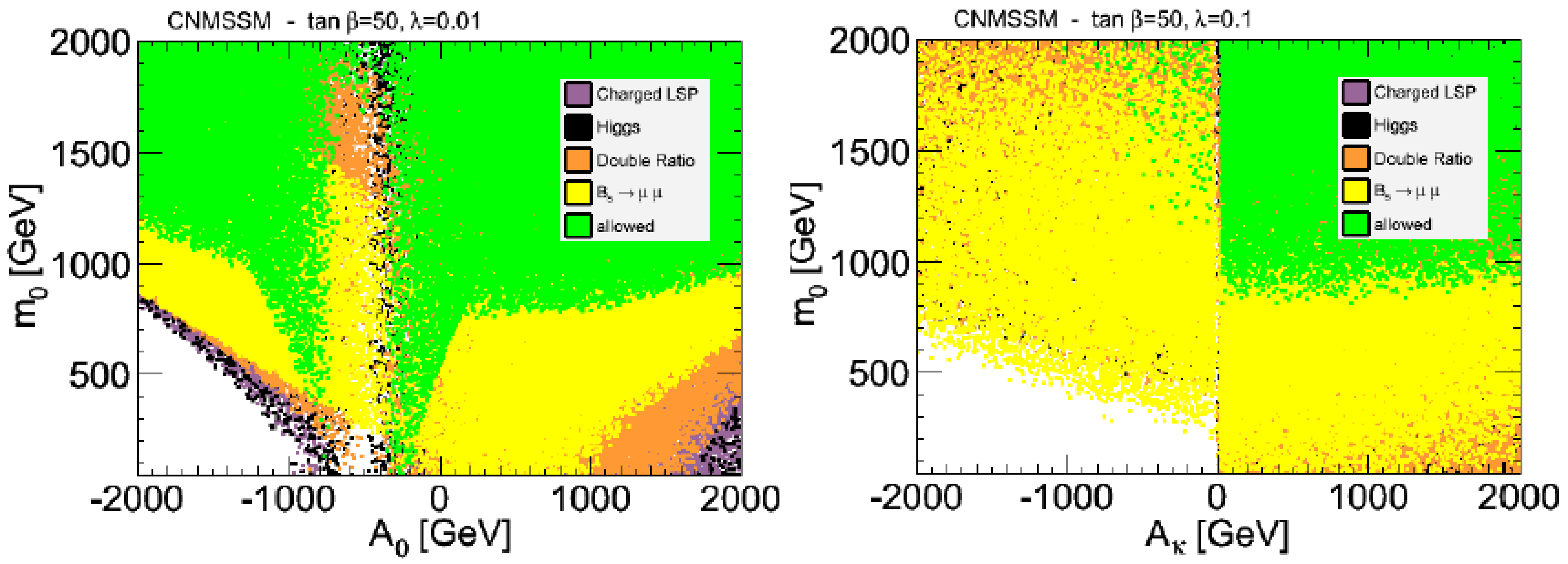




$v_u/v_d \lesssim 0.12\ M_{A0}$ [GeV] regardless the value of other parameters (constraint stronger depending on the value of the other params…), perhaps with the exception of a small vertical region at low M

~CNMSSM

$$\{m_0, m_{1/2}, A_0, A_\kappa, \lambda, \tan\beta, \mathrm{sgn}(\mu)\}$$



The extra parameters that are in NMSSM affect strongly $B_s \to \mu\mu$. The plots sometimes look quite complicated…

~CNMSSM

$$\{m_0, m_{1/2}, A_0, A_\kappa, \lambda, \tan\beta, \mathrm{sgn}(\mu)\}$$

The constraints are more pronounced at:

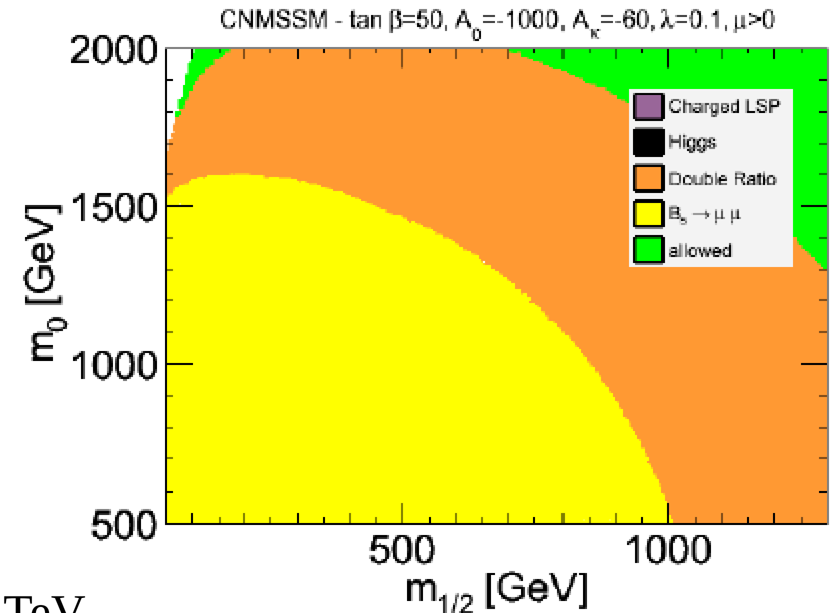
•High tanβ

•High λ

•Negative A_K.

•Negative A_0.

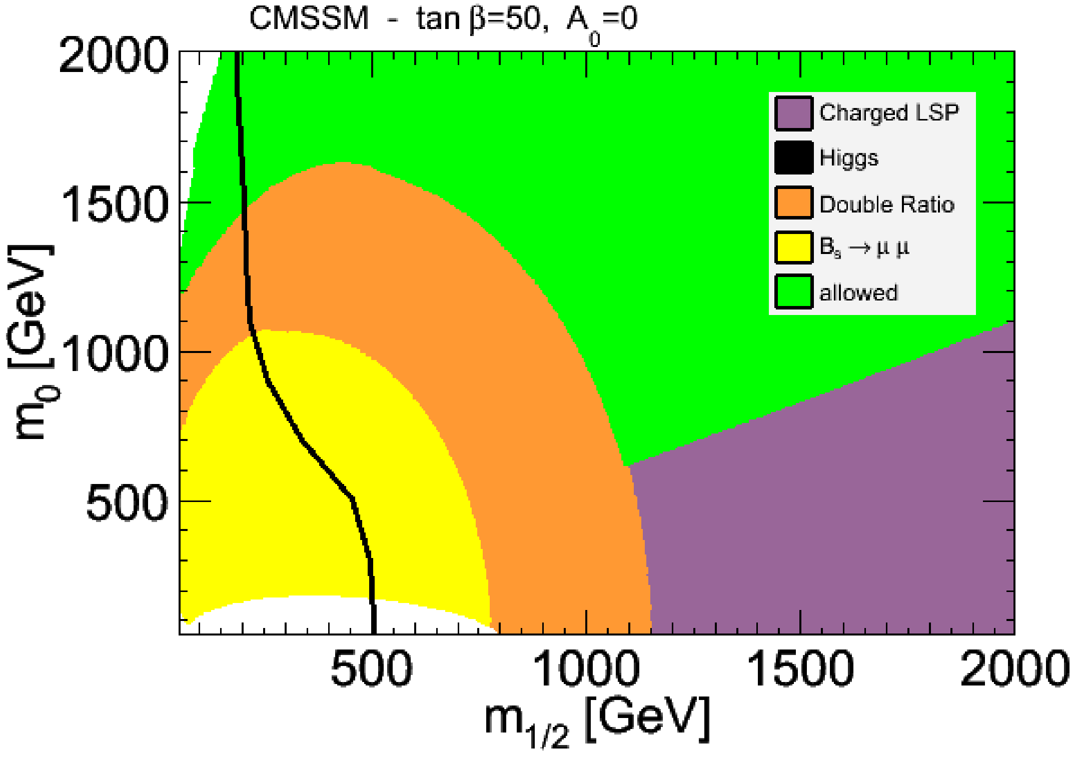
In some cases it can impose SUSY masses > 2 TeV



In summary…

- Current limits from CMS + LHCb $B_s \rightarrow \mu\mu$ impact SUSY parameter space

- Constraints in high $\tan\beta$ can be superior to those from direct searches



Black line: CMS direct searches

What does $\mathcal{B}_s \to \mu\mu$ add on top of other observables?

Supersymmetry in light of 1/fb of LHC data 1110.3568
(submitted to EPJC)

MasterCode Collab. : O. Buchmueller, R. Cavanaugh, A. De Roeck, M.J. Dolan, J.R. Ellis, H. Flacher, S. Heinemeyer, D. Martinez Santos, K.A. Olive, S. Rogerson, F.J. Ronga, G. Weiglein

Fit CMSSM and NUHM-I to several observables

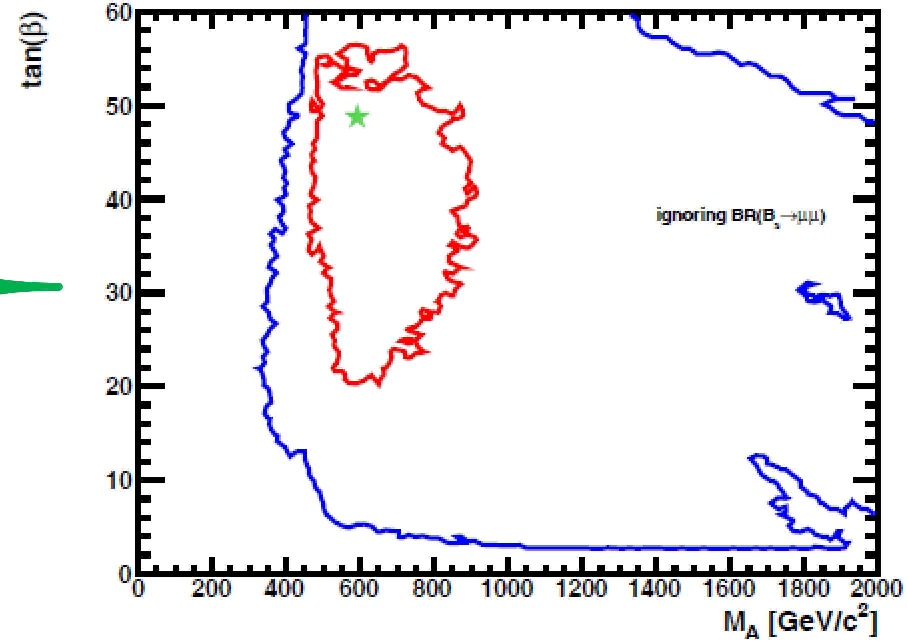
MasterCode fit

m_t [GeV]
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$
M_Z [GeV]
Γ_Z [GeV]
$\sigma^0_{\rm had}$ [nb]
R_l
$A_{\rm fb}(\ell)$
$A_\ell(P_\tau)$
$R_{\rm b}$
$R_{\rm c}$
$A_{\rm fb}(b)$
$A_{\rm fb}(c)$
A_b
A_c
A_ℓ(SLD)
$\sin^2\theta^\ell_{\rm w}(Q_{\rm fb})$
M_W [GeV]
$a_\mu^{\rm EXP} - a_\mu^{\rm SM}$
M_h [GeV]

$\mathrm{BR}^{\rm EXP/SM}_{b\to s\gamma}$
~~$\mathrm{BR}(B_s \to \mu^+\mu^-)$~~
$\mathrm{BR}^{\rm EXP/SM}_{B\to\tau\nu}$
$\mathrm{BR}(B_d \to \mu^+\mu^-)$
$\mathrm{BR}^{\rm EXP/SM}_{B\to X_s\ell\ell}$
$\mathrm{BR}^{\rm EXP/SM}_{K\to\mu\nu}$
$\mathrm{BR}^{\rm EXP/SM}_{K\to\pi\nu\bar\nu}$
$\Delta M^{\rm EXP/SM}_{B_s}$
$\frac{\Delta M^{\rm EXP/SM}_{B_s}}{\Delta M^{\rm EXP/SM}_{B_d}}$
$\Delta\epsilon^{\rm EXP/SM}_K$
$\Omega_{\rm CDM}h^2$
$\sigma_p^{\rm SI}$
jets + $\not{E}_T$
$H/A, H^\pm$

NUHM-I

CMSSM + { |μ| }



★ Minimum

1 σ contour

2 σ contour

MasterCode fit

m_t [GeV]
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$
M_Z [GeV]
Γ_Z [GeV]
$\sigma^0_{\rm had}$ [nb]
R_l
$A_{\rm fb}(\ell)$
$A_\ell(P_\tau)$
$R_{\rm b}$
$R_{\rm c}$
$A_{\rm fb}(b)$
$A_{\rm fb}(c)$
A_b
A_c
A_ℓ(SLD)
$\sin^2\theta^\ell_{\rm w}(Q_{\rm fb})$
M_W [GeV]
$a_\mu^{\rm EXP} - a_\mu^{\rm SM}$
M_h [GeV]

$\mathrm{BR}^{\rm EXP/SM}_{b\to s\gamma}$
$\mathrm{BR}(B_s \to \mu^+\mu^-)$
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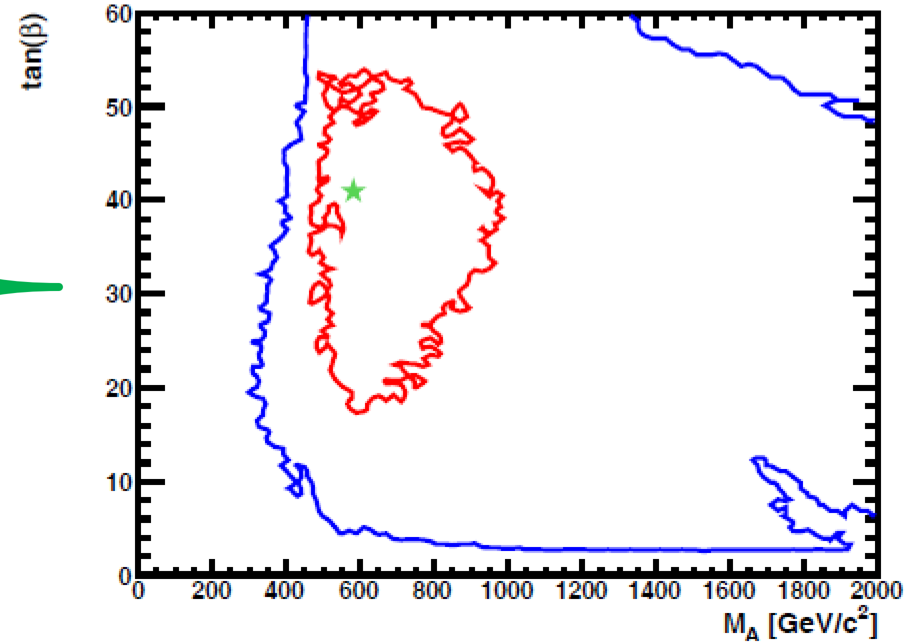
$\mathrm{BR}(B_d \to \mu^+\mu^-)$
$\mathrm{BR}^{\rm EXP/SM}_{B\to X_s\ell\ell}$
$\mathrm{BR}^{\rm EXP/SM}_{K\to\mu\nu}$
$\mathrm{BR}^{\rm EXP/SM}_{K\to\pi\nu\bar\nu}$
$\Delta M^{\rm EXP/SM}_{B_s}$
$\frac{\Delta M^{\rm EXP/SM}_{B_s}}{\Delta M^{\rm EXP/SM}_{B_d}}$
$\Delta\epsilon^{\rm EXP/SM}_K$
$\Omega_{\rm CDM}h^2$
$\sigma_p^{\rm SI}$
jets + $\not\!\!E_T$
$H/A, H^\pm$

NUHM-I

CMSSM + { |μ| }



★ Minimum

1 σ contour

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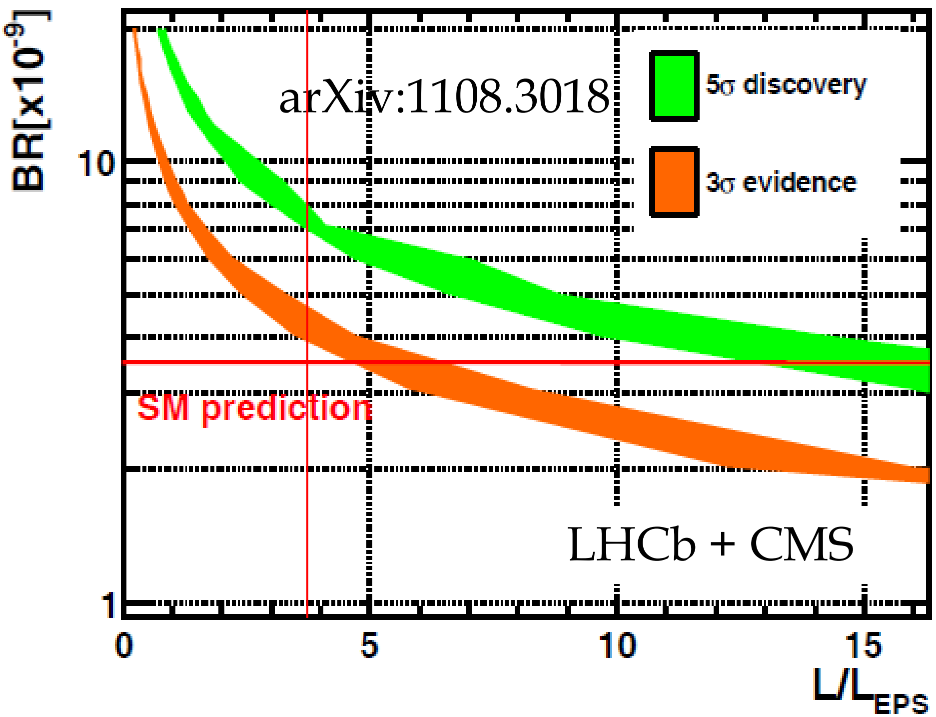
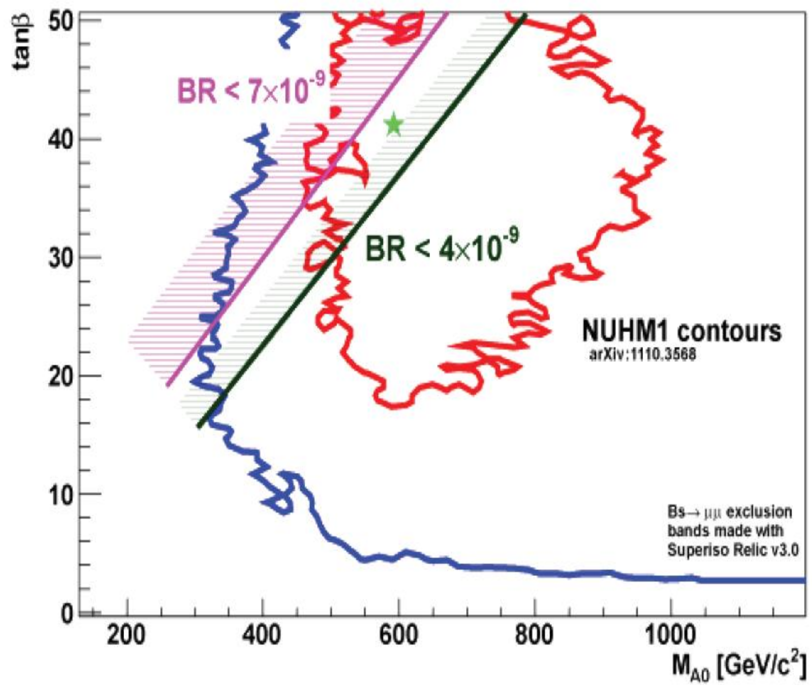
Prospects





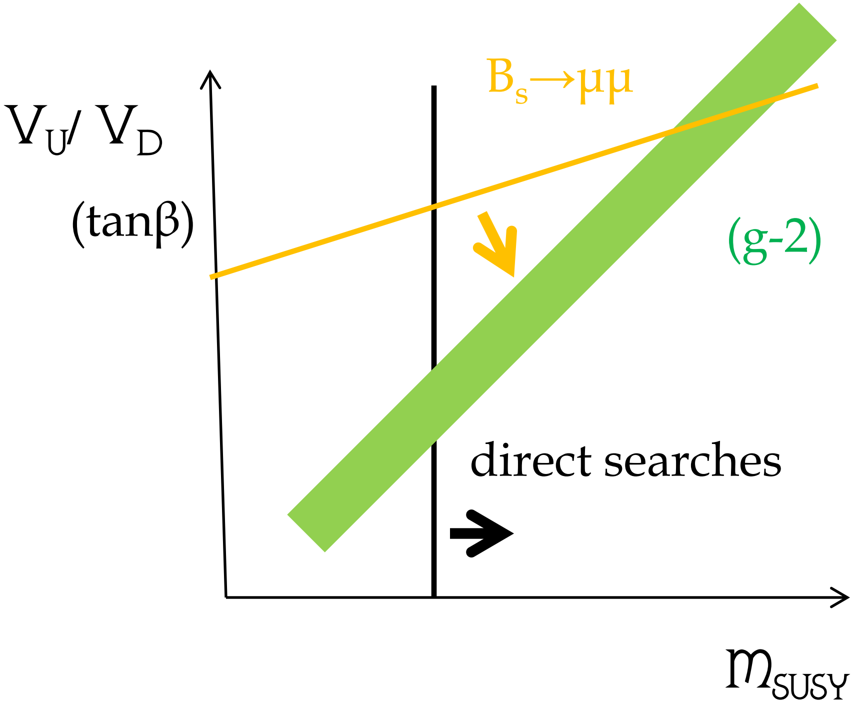
There is big chances that LHC finds $B_s \to \mu\mu$ at 3-5 sigma before the end of 3.5 TeV run. Even (with a bit of luck/improvements/ATLAS entering in the game …) by the winter conferences

Conclusions

CMS & LHCb limit $B_s \to \mu\mu$ puts strong constraints on high tanβ

Direct searches push towards higher masses of SUSY particles. To accommodate this with (g-2) one prefers high tanβ and there enters in "contradiction" with $B_s \to \mu\mu$

LHC has a big chance of discover $B_s \to \mu\mu$ before the end of 3.5 TeV run, constraining NP parameter spaces depending on the actual measurement



PS: For those who have seen Xabier's talk yesterday (LHCb preliminary results for HCP) : CMS(EPS)+LHCb(HCP) does not visibly change the limit w.r.t CMS(EPS)+LHCb(EPS). The signal significance and preferred BR get higher, though.

Backup

SUSY breaking terms

$$L_{SOFT} = -\{\tilde{l}^{*}_{Li}(M^{2}_{\tilde{l}})^{ij}\tilde{l}_{Lj} + \tilde{q}^{*}_{Li}(M^{2}_{\tilde{q}})^{ij}\tilde{q}_{Lj} + \tilde{u}^{*}_{Ri}(M^{2}_{\tilde{u}R})^{ij}\tilde{u}_{Rj} + \tilde{d}^{*}_{Ri}(M^{2}_{\tilde{d}R})^{ij}\tilde{d}_{Rj} + \tilde{e}^{*}_{Ri}(M^{2}_{\tilde{e}R})^{ij}\tilde{e}_{Rj}$$

$$+ m^{2}_{Hu}|H_u|^2 + m^{2}_{Hd}|H_d|^2 + (B\cdot\mu H_u H_d + h.c.) + (H_d[\tilde{l}^{*}_{Li}(h_{\tilde{e}}A_{\tilde{e}})^{ij}\tilde{e}_{Rj} + \tilde{q}^{*}_{Li}(h_{\tilde{d}}A_{\tilde{d}})^{ij}\tilde{d}_{Rj}] +$$

$$H_u\tilde{q}^{*}_{Li}(h_{\tilde{u}}A_{\tilde{u}})^{ij}\tilde{u}_{Rj} + h.c.) + \frac{1}{2}(m_{\tilde{B}}\bar{\tilde{B}}^{o}P_L\tilde{B}^{o} + m^{*}_{\tilde{B}}\bar{\tilde{B}}^{o}P_R\tilde{B}^{o}) + \frac{1}{2}(m_{\tilde{W}}\bar{\tilde{\vec{W}}}P_L\tilde{\vec{W}} + m^{*}_{\tilde{W}}\bar{\tilde{\vec{W}}}P_L\tilde{\vec{W}})$$

$$+\frac{1}{2}(m_{\tilde{g}}\bar{\tilde{g}}^{a}P_L\tilde{g}^{a} + m^{*}_{\tilde{g}}\bar{\tilde{g}}^{a}P_R\tilde{g}^{a})\}$$

CMSSM

$$m_{\tilde{B}}(M_U) = m_{\tilde{W}}(M_U) = m_{\tilde{g}}(M_U) \equiv m_{1/2}$$

$$M_{\tilde{l}}^2(M_U) = M_{\tilde{q}}^2(M_U) \equiv m_0^2 I_3$$

$$M_{\tilde{u}}^2(M_U) = M_{\tilde{e}}^2(M_U) = M_{\tilde{d}}^2(M_U) = m_0^2 I_3$$

$$m_{Hu}^2 = m_{Hd}^2 = m_0^2$$

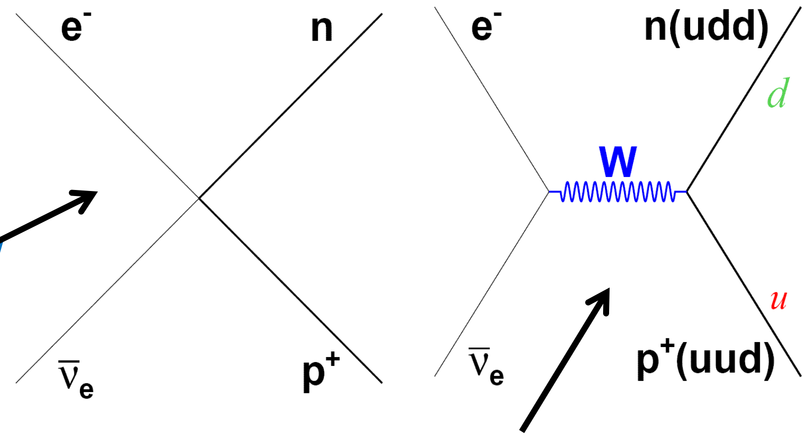
$$A_{\tilde{u}}(M_U) = A_{\tilde{e}}(M_U) = A_{\tilde{d}}(M_U) \equiv A_0 I_3$$

Wilson coefficients

Hadronic weak decays are often studied in terms of effective hamiltonians of local operators Q_i:

$$H_{eff} \propto \sum_i C_i \hat{Q}_i$$

effective local theory



underlying "fundamental" theory (SM)

Degrees of freedom of exchanged particles are integrated out giving rise to the **Wilson coefficients C_i**.

An **example** of similar approach: **Fermi's theory of neutron decay**

BR($B_s \rightarrow \mu\mu$) expressed in eff. th. as:

$$BR(B_q \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3}|V_{tb}^*V_{tq}|^2\,\tau_{Bq}M_{Bq}^3 f_{Bq}^2\sqrt{1-\frac{4m_\mu^2}{M_{Bq}^2}}\times\left\{M_{Bq}^2\left(1-\frac{4m_\mu^2}{M_{Bq}^2}\right)C_S^2+\left[M_{Bq}C_P+\frac{2m_\mu}{M_{Bq}}C_{10}\right]^2\right\}$$

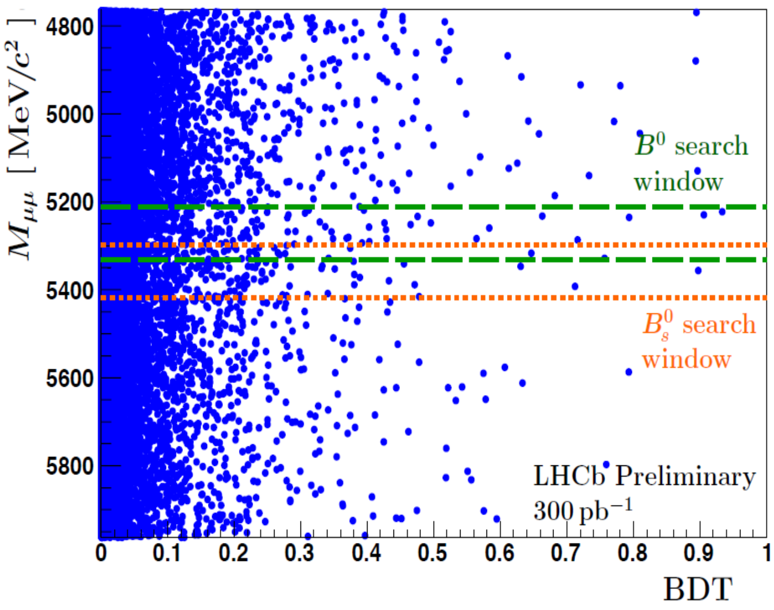
$C_{P,S,10}$ (pseudoscalar, scalar and axial) **depend on the underlying model (SM, SUSY…)**

Analysis strategy

LHCb-CONF-2011-037

- Classification of $B_{s,d} \rightarrow \mu\mu$ events in bins of a 2D space
  - Invariant mass of the μμ pair
  - BDT variable combining geometrical and kinematical information about the event.

•Flat distributed for signal, background peaks at 0

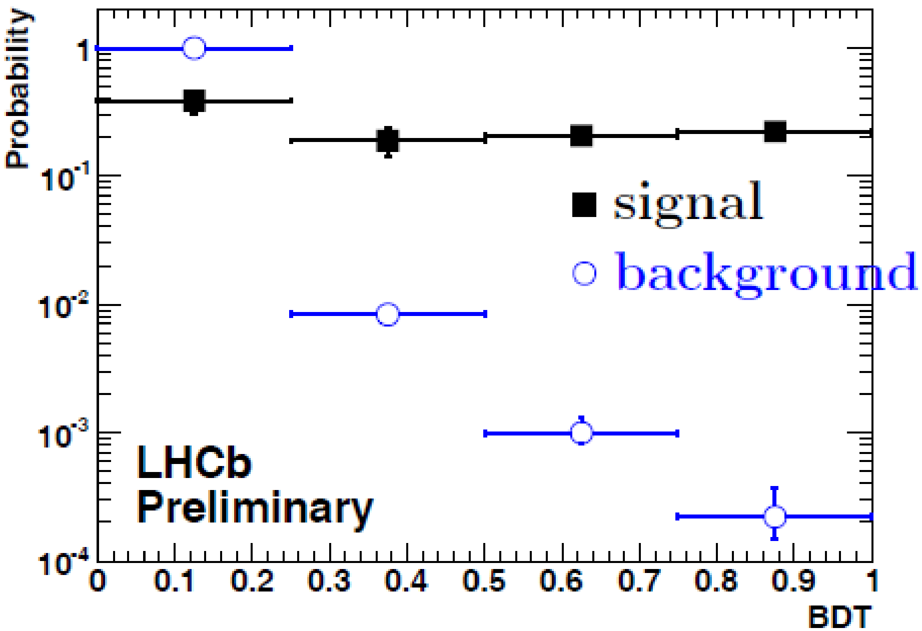


- Control channels to get signal and background expectations w/o relying on simulation

- Compare expectations with observed distribution. Results combined using CL_s method

pdf calibration

LHCb-CONF-2011-037



- BDT is trained using MC samples of $B_s \rightarrow \mu\mu$ signal and bb $\rightarrow \mu\mu$ background.
- **Distributions taken from data to not rely on the accuracy of the simulation**

- BDT distribution of real signal obtained by looking at $B \rightarrow h^+h^-$ (h = K, π) in real data.
- Invariant mass distribution for signal is obtained from control channels , $B \rightarrow h^+h^-$, dimuon resonances.
- Background distribution is obtained from data by interpolating from mass sidebands in GL bins

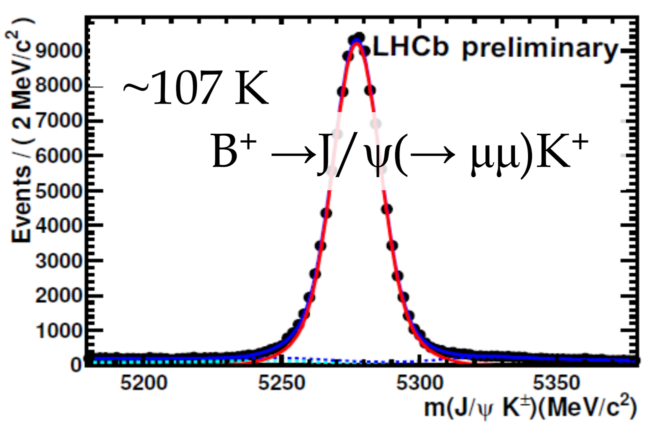
Normalization

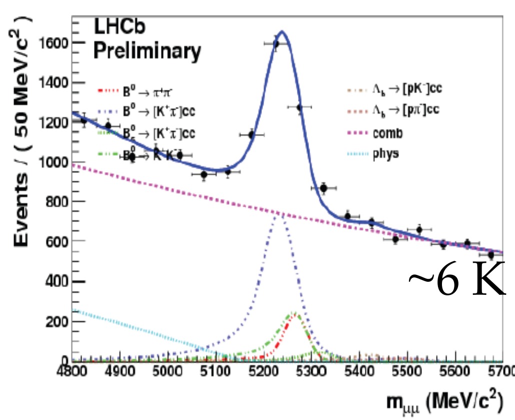
- Observed/excluded signal yield is translated into an observed (excluded) BR via normalization to a known B decay

- Three different channels are used, each one with different (dis)advantages

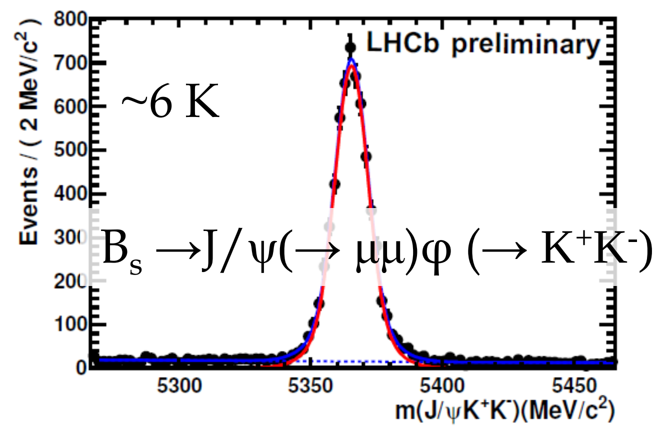
	$\alpha^{cal}_{B_d \to \mu^+\mu^-}$ $(\times 10^{-10})$	$\alpha^{cal}_{B_s \to \mu^+\mu^-}$ $(\times 10^{-9})$
$B^+ \to J/\psi K^+$	2.58 ± 0.16	0.966 ± 0.096
$B^0_s \to J/\psi \phi$	3.39 ± 0.98	1.27 ± 0.35
$B^0 \to K^+\pi^-$	2.47 ± 0.57	0.92 ± 0.22

$\alpha \sim 1\text{x}10^{-9} \leftrightarrow 3.5$ expected SM events!





$B_d \to K^+\pi^-$



Results

LHCb-CONF-2011-037

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) \; < \; 1.3(1.6) \times 10^{-8} \text{ at } 90\,\%(95\,\%) \text{ C.L.},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) \; < \; 4.2(5.1) \times 10^{-9} \text{ at } 90\,\%(95\,\%) \text{ C.L.}$$

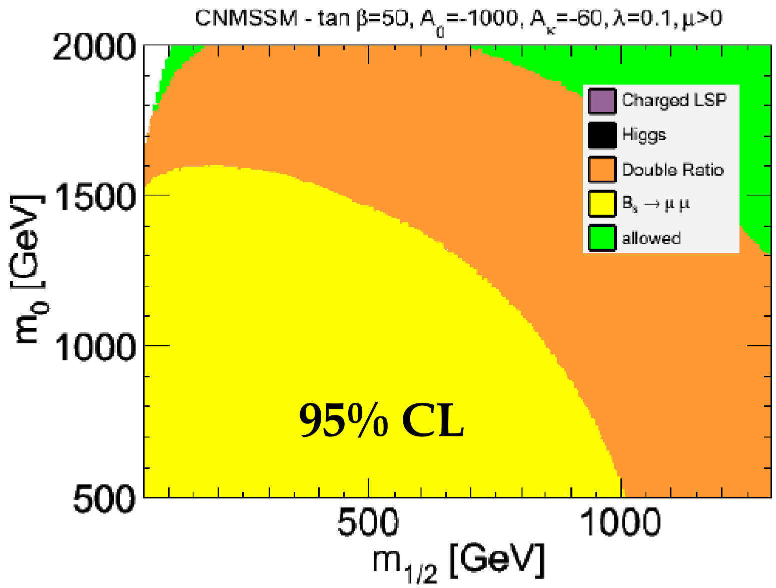
Combining with the 37 pb^{-1} of 2010 analysis:

$$\mathcal{B}(B^0_s \to \mu^+\mu^-)(2010+2011) \; < \; 1.2(1.5) \times 10^{-8} \text{ at } 90\,\%(95\,\%) \text{ C.L.}$$

Implications

- arXiV:1108.3018. (F. Mahmoudi et al.) implications of CMS+LHCb combination (together with $B \to \tau\nu$, $D \to \mu\nu$, $D_s \to \mu\nu$) in: CMSSM, NUHM, mAMSB, mGMSB, CNMSSM)

In short summary, the constraints from $Bs \to \mu\mu$ (or the double ratio) are quite strong for **high tanβ**(~50), in CMSSM one needs masses of >~ 1 TeV compatible with $Bs \to \mu\mu$ upper limit.

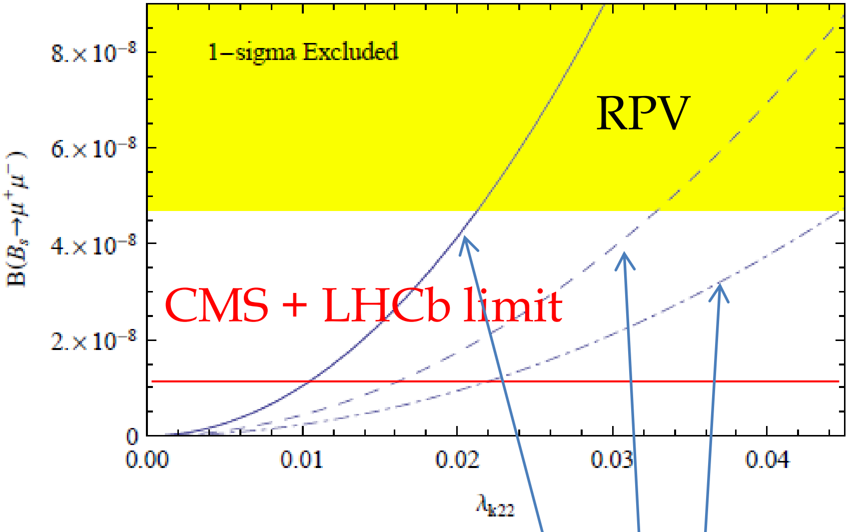


specially good example ☺

Implications

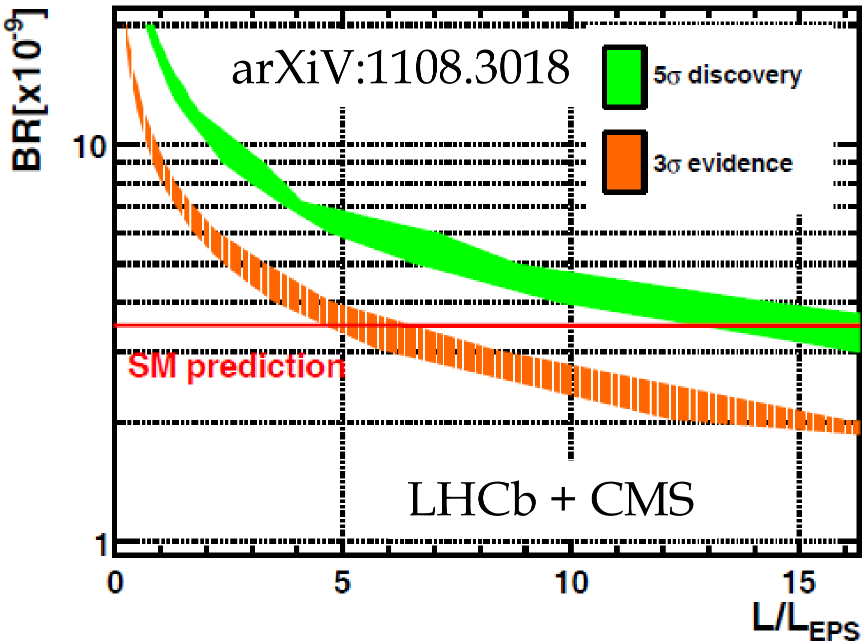
- arXiv:1102.0009. (E. Golowich et al.) $B_s \to \mu\mu$ is studied in different NP scenarios
- Strongest constraints are found in RPV and **N**MSSM-like models.

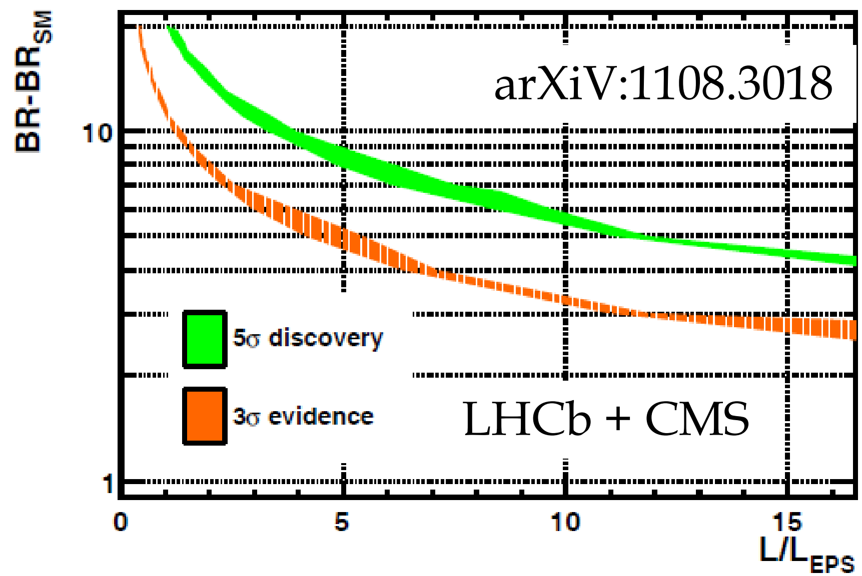
- Current limit would not constrain
  - Z′ models
  - family horizontal symmetries



sneutrino mass = 100, 150, 200

Prospects





(L_{EPS} = 1.14 fb^{-1} CMS, 0.34 fb^{-1} LHCb)

- A 3σ is quite likely to happen before end of 7 TeV run (even a 5σ is likely)
- A NP 3σ can happen if $BR(B_s \rightarrow \mu\mu) \geq \sim 2xBR(B_s \rightarrow \mu\mu)_{SM}$

Conclusions

- First $B_d \rightarrow K^*\mu\mu$ results from LHCb show very good agreement with SM prediction

- This could favor strongly $C_7 \sim C_7$ SM solution

- Stay tuned for analysis with more data ~by Moriond.

- CMS+LHCb limit on $BR(B_s \rightarrow \mu\mu)$ imposes strong constraints on SUSY at high $\tan\beta$ (or in RPV), superior to direct searches in some cases.

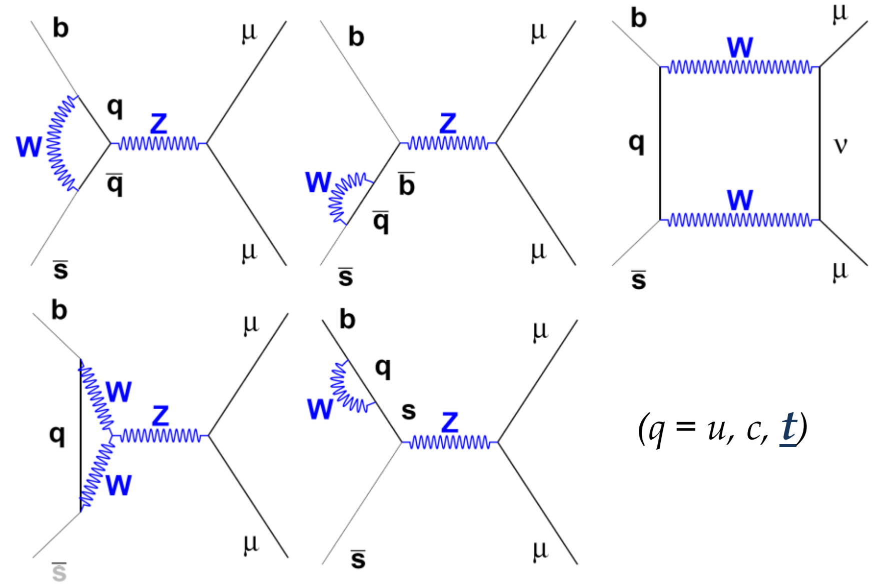
- $B_s \rightarrow \mu\mu$ signal evidence/discovery will likely happen before end of 2012. NP contributions down to $\sim 3\mathrm{x}10^{-9}$ (on top of SM) can be disentangled at 3 sigma before the end of 7 TeV run.

- Once $B_{s(\mathrm{or}\ d)} \rightarrow \mu\mu$ is observed the ratio Bs/Bd is a strong test of MFV.

SM and New Physics

This decay is very suppressed in SM :

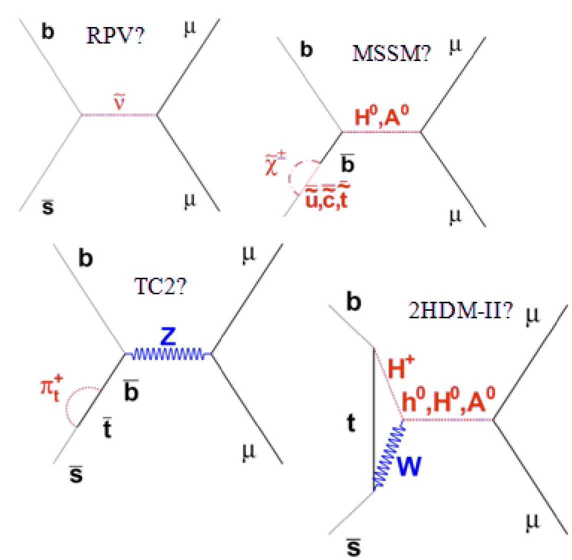
$$BR(B_s \rightarrow \mu\mu) = (3.5 \pm 0.3)x10^{-9}$$
$$BR(B_d \rightarrow \mu\mu) = (1.0 \pm 0.1)x10^{-10}$$



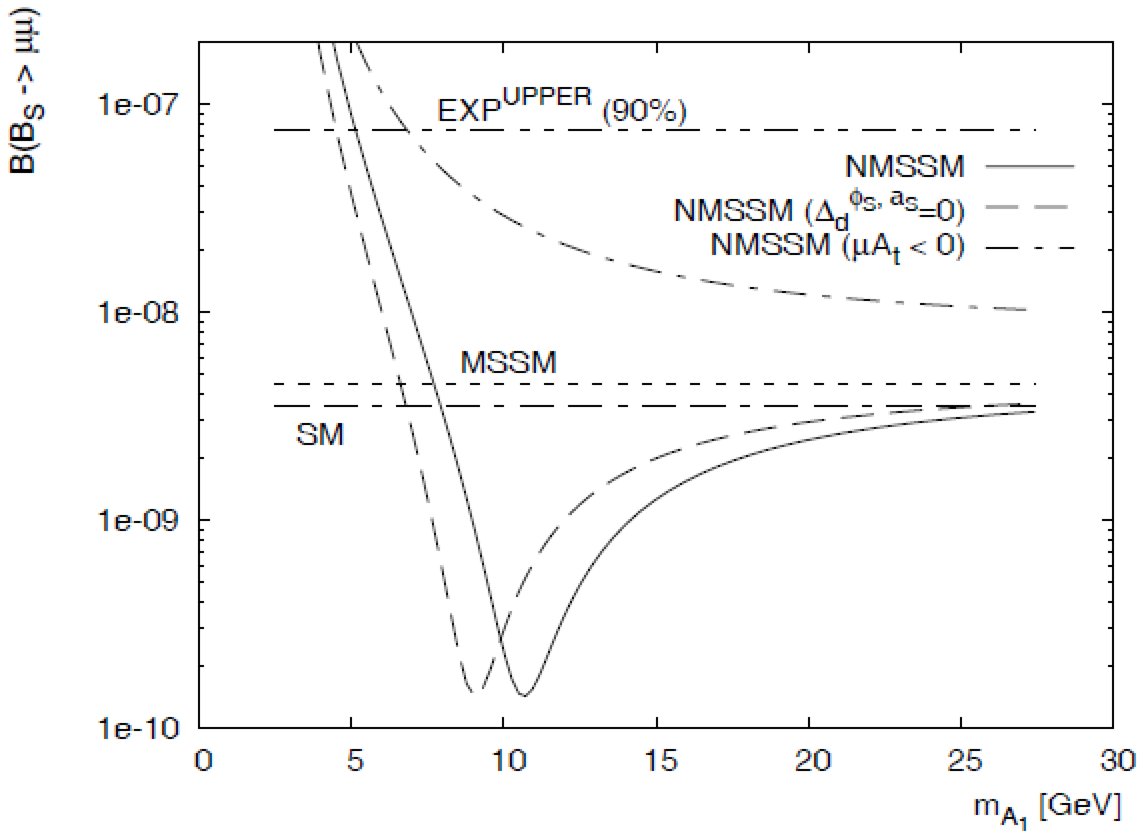
But in NP models it can take any value from << SM (e.g, some NMSSM) up to current experimental upper limit (e.g. SUSY at high tanβ).

→ ***Whatever the actual value is, it will have an impact on NP searches***

+?



Backup


B(B_S -> μμ)
1e-07
1e-08
1e-09
1e-10
EXP^UPPER (90%)
NMSSM
NMSSM (Δ_d^{φS, aS}=0)
NMSSM (μA_t < 0)
MSSM
SM
0
5
10
15
20
25
30
m_{A_1} [GeV]

sensitivity