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

Diego Martinez Santos (CERN)
Introduction

- $B_s \rightarrow \mu \mu$ 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 $\text{BR}(B_s \rightarrow \mu \mu) < \sim 3 \times \text{SM}$.

- This talk: implications of such a measurement
  - $B_s \rightarrow \mu \mu$ alone
  - $B_s \rightarrow \mu \mu$ on top of other observables

Disclaimer: I’m an experimentalist. Sorry if some of this is inaccurate / wrong!
Decay Physics (SM)

Model ~independent expression:

\[
BR(B_q \rightarrow \mu^+ \mu^-) = \frac{G_F^2 \alpha^2}{64\pi^3} |V_{tb}^* V_{tq}|^2 \tau_{B_q} M_{B_q}^3 f_{B_q}^2 \sqrt{1 - \frac{4m_\mu^2}{M_{B_q}^2}} \times \\
\times \left\{ M_{B_q}^2 \left( 1 - \frac{4m_\mu^2}{M_{B_q}^2} \right) C_s^2 + \left[ M_{B_q} C_p + \frac{2m_\mu}{M_{B_q}} C_{10} \right]^2 \right\} \\
\text{SM} \quad \text{SM}
\]

\( C_{S,P} \rightarrow \text{scalar and pseudo scalar are negligible in SM} \)
\( C_{10} \) gives the only relevant contribution

This decay is very suppressed in SM: \( BR(B_s \rightarrow \mu\mu) = (3.5 \pm 0.3) \times 10^{-9} \)
New Physics effects

NP

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

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

\[ \rightarrow \text{Whatever the actual value is, it will have an impact on NP searches} \]

(For a collection of references of Bsmm in different models see CERN-THESIS-2010-068)
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<td>( \text{BR}(B_s \to \mu\mu) \gg SM )</td>
<td>Big enhancement from NP in scalar sector, SUSY high ( \tan\beta )</td>
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<td>( \text{BR}(B_s \to \mu\mu) \neq SM )</td>
<td>SUSY (( C_S, C_P )), ED’s, LHT, TC2 (( C_{10} ))…</td>
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<td>( \text{BR}(B_s \to \mu\mu) \sim SM )</td>
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<td>CMFV ruled out. New FCNC sources fully independent of CKM matrix (RPV SUSY, ED’s etc…)...</td>
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LHCb & CMS combination (EPS 2011)

CMS limit (1.9x10^{-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 \rightarrow \mu\mu) < 0.9x10^{-8} @ 90% CL
BR(B_s \rightarrow \mu\mu) < 1.1x10^{-8} @ 95% CL

(rem. SM ~ 3.5x10^{-9})

The observed distribution of events agrees very well with bkg +SM
CL_b \sim 92 % (\Rightarrow Probability of bkg-anlone is \sim 8%. Not enough to claim discovery, though)
New Physics effects

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1. Gauge part = SM:
   \[ G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_{EM} \]

2. Supersymmetry: SM particles \( \Leftrightarrow \) “superpartners” (particle + superpartner \( \rightarrow \) superfield):
   - SM fermion \( \Leftrightarrow \) SUSY boson (sfermions: selectron, squark …)
   - SM boson / higgses \( \Leftrightarrow \) SUSY fermion (inos: gluino, photino …)

\( \rightarrow \) Broken (superpartners not been seen yet \( \rightarrow \) heavier): All renormalizable SUSY breaking terms are considered (in principle) \( \rightarrow \) 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: \( R = -1 \).
   \( \rightarrow \) Superpartners produced/annihilated in pairs \( \rightarrow \) 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
Similar to MSSM, but the interaction in the .. term

\[ \mu \hat{H}_u \hat{H}_d \rightarrow \lambda \hat{S} \hat{H}_u \hat{H}_d \]

happens through a Higgs singlet

(and then you have few terms in the lagrangian related to this higgs singlet)
The decay $B_s \rightarrow \mu \mu$: 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, \text{sgn}(\mu)\}

\[ R \equiv \frac{\eta}{\eta_{\text{SM}}} \quad \eta \equiv \frac{\text{BR}(B_s \to \mu^+\mu^-)}{\text{BR}(B_u \to \tau\nu)} \div \frac{\text{BR}(D_s \to \tau\nu)}{\text{BR}(D \to \mu\nu)} \]

high \tan\beta
**CMSSM**

\[ \{m_0, m_{1/2}, A_0, \tan \beta, \text{sgn}(\mu)\} \]

\[ R \equiv \frac{\eta}{\eta_{\text{SM}}} \quad \eta \equiv \frac{\text{BR}(B_s \rightarrow \mu^+\mu^-)}{\text{BR}(B_u \rightarrow \tau\nu)} \Bigg/ \frac{\text{BR}(D_s \rightarrow \tau\nu)}{\text{BR}(D \rightarrow \mu\nu)} \]
NUHM-II

CMSSM + \{ |\mu|, m_A \}

\[ \frac{v_u}{v_d} \approx 0.12 \, M_{A0} \, [\text{GeV}] \] 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
The extra parameters that are in NMSSM affect strongly $B_s \rightarrow \mu \mu$. The plots sometimes look quite complicated…
The constraints are more pronounced at:

• High tan\(\beta\)

• High \(\lambda\)

• Negative \(A_K\).

• Negative \(A_0\).

In some cases it can impose SUSY masses > 2 TeV
In summary...

• Current limits from CMS + LHCb $B_s \to \mu\mu$ impact SUSY parameter space

• Constraints in high $\tan\beta$ can be superior to those from direct searches
What does $B_s \rightarrow \mu\mu$ add on top of other observables?

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


Fit CMSSM and NUHM-I to several observables
### MasterCode fit

#### NUHM-I

CMSSM + \{ |\mu| \}

#### Table

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<th>Units</th>
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<tbody>
<tr>
<td>$m_t$</td>
<td>[GeV]</td>
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<tr>
<td>$\Delta \alpha^{(S)}_{\text{had}} (M_Z)$</td>
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</tr>
<tr>
<td>$M_Z$</td>
<td>[GeV]</td>
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<tr>
<td>$\Gamma_Z$</td>
<td>[GeV]</td>
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<tr>
<td>$\sigma^0_{\text{had}}$</td>
<td>[nb]</td>
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<tr>
<td>$R_t$</td>
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<tr>
<td>$A_{\text{fb}}(\ell)$</td>
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<tr>
<td>$A_{\ell}(P_{\tau})$</td>
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<td>$R_b$</td>
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<td>$R_c$</td>
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<td>$A_{\text{fb}}(b)$</td>
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<td>$A_c$</td>
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<tr>
<td>$A_{\ell}(\text{SLD})$</td>
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<tr>
<td>$\sin^2 \theta^e_W (Q_{\text{fb}})$</td>
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<tr>
<td>$M_W$</td>
<td>[GeV]</td>
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<tr>
<td>$a_{\mu}^{\text{EXP}} - a_{\mu}^{\text{SM}}$</td>
<td></td>
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<td>$M_h$</td>
<td>[GeV]</td>
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#### Diagram

- **Minimum**
- 1 σ contour
- 2 σ contour
**MasterCode fit**

**NUHM-I**

CMSSM + \{ |\mu| \}

- ★ Minimum
- 1σ contour
- 2σ contour
Prospects

There is big chances that LHC finds $B_s \rightarrow \mu\mu$ 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 $B_s\rightarrow\mu\mu$ puts strong constraints on high $\tan\beta$

Direct searches push towards higher masses of SUSY particles. To accommodate this with $(g-2)$ one prefers high $\tan\beta$ and there enters in “contradiction” with $B_s\rightarrow\mu\mu$

LHC has a big chance of discover $B_s\rightarrow\mu\mu$ 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

\[ L_{\text{SOFT}} = -\{ \tilde{l}_{Li}^* (M_i^2)^j l_{Lj} + \tilde{q}_{Li}^* (M_q^2)^j q_{Lj} + \tilde{u}_{Ri}^* (M_{\tilde{u}R}^2)^j u_{Rj} + \tilde{d}_{Ri}^* (M_{\tilde{d}R}^2)^j d_{Rj} + \tilde{e}_{Ri}^* (M_{\tilde{e}R}^2)^j e_{Rj} \]
\[ + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + (B \cdot \mu H_u H_d + \text{h.c.}) + (H_d [\tilde{l}_{Li}^* (h_{\tilde{u}A_{\tilde{u}}})^j e_{Rj} + \tilde{q}_{Li}^* (h_{\tilde{d}A_{\tilde{d}}})^j d_{Rj}] + \]
\[ H_u \tilde{q}_{Li}^* (h_{\tilde{u}A_{\tilde{u}}})^j \tilde{u}_{Rj} + \text{h.c.}) + \frac{1}{2} (m_{\tilde{B}B}^* P_L \tilde{B}^o + m_{\tilde{B}B}^* \tilde{P}_R B^o) + \frac{1}{2} (m_{\tilde{W}W}^* WP_{L\tilde{W}} + m_{\tilde{W}W}^* WP_{\tilde{L}\tilde{W}}) \]
\[ + \frac{1}{2} (m_{\tilde{g}g}^* P_L \tilde{g}^a + m_{\tilde{g}g}^* \tilde{P}_R g^a) \} \]
CMSSM

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

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

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

$$m_{H_u}^2 = m_{H_d}^2 = m_0^2$$

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

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

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

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

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

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

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

- Classification of $B_{s,d} \rightarrow \mu\mu$ events in bins of a 2D space
  - Invariant mass of the $\mu\mu$ 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 $\text{CL}_{s}$ method

LHCb-CONF-2011-037
BDT is trained using MC samples of $B_s \rightarrow \mu\mu$ signal and $b\bar{b} \rightarrow \mu\mu$ background.

Distributions taken from data to not rely on the accuracy of the simulation.

BDT distribution of real signal obtained by looking at $B \rightarrow h^+h^-$ ($h = K, \pi$) 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

<table>
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<tr>
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<th>$\alpha_{B_d \to \mu^+\mu^-}^{\text{cal}}$</th>
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<tr>
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<td>$(\times 10^{-10})$</td>
<td>$(\times 10^{-9})$</td>
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<tr>
<td>$B^+ \to J/\psi K^+$</td>
<td>$2.58 \pm 0.16$</td>
<td>$0.966 \pm 0.096$</td>
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<tr>
<td>$B_s^0 \to J/\psi \phi$</td>
<td>$3.39 \pm 0.98$</td>
<td>$1.27 \pm 0.35$</td>
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<tr>
<td>$B^0 \to K^+\pi^-$</td>
<td>$2.47 \pm 0.57$</td>
<td>$0.92 \pm 0.22$</td>
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$\alpha \sim 1 \times 10^{-9} \leftrightarrow 3.5$ expected SM events!

- $\sim 107$ K
  - $B^+ \to J/\psi(\to \mu\mu)K^+$

- $\sim 6$ K
  - $B_s \to J/\psi(\to \mu\mu)\phi (\to K^+K^-)$
  - $B_d \to K^+\pi^-$
**Results**

\[
\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) < 1.3(1.6) \times 10^{-8} \text{ at } 90\% (95\%) \text{ C.L.,}
\]
\[
\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 4.2(5.1) \times 10^{-9} \text{ at } 90\% (95\%) \text{ C.L.}
\]

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

\[
\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)(2010 + 2011) < 1.2(1.5) \times 10^{-8} \text{ at } 90\% (95\%) \text{ C.L.}
\]
**Implications**

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

In short summary, the constraints from $B_s \rightarrow \mu \mu$ (or the double ratio) are quite strong for high $\tan\beta$($\sim$50), in CMSSM one needs masses of >~1 TeV compatible with $B_s \rightarrow \mu \mu$ upper limit.
Implications

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

- Current limit would not constrain
  - $Z'$ models
  - family horizontal symmetries

![Graph showing CMS + LHCb limit with sneutrino mass = 100, 150, 200]
Prospects

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→μμ) ≥ ~2xBR(B_s→μμ )_{SM}

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

• First $B_d \to K^* \mu\mu$ 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 $BR(B_s \to \mu\mu)$ imposes strong constraints on SUSY at high $\tan\beta$ (or in RPV), superior to direct searches in some cases.

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

• Once $B_s(\text{or } d) \to \mu\mu$ is observed the ratio $B_s/B_d$ is a strong test of MFV.
**SM and New Physics**

This decay is very suppressed in SM:

\[
\text{BR}(B_s \rightarrow \mu\mu) = (3.5 \pm 0.3) \times 10^{-9}
\]
\[
\text{BR}(B_d \rightarrow \mu\mu) = (1.0 \pm 0.1) \times 10^{-10}
\]

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 tan\(\beta\)).

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