$B_s \rightarrow \mu^+ \mu^-$ versus Direct Higgs Searches at Hadron Colliders

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and
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$B_s \rightarrow \mu^+ \mu^-$ versus Direct Higgs Searches at Hadron Colliders


~ Direct search for Higgs bosons at the LHC

$pp \rightarrow b\phi^0 \rightarrow b\mu^+ \mu^- + X, \phi^0 = H^0, h^0, A^0$

~ Indirect search for Higgs bosons in

$B_s \rightarrow \mu^+ \mu^-$
The Standard Model Higgs Boson

• In the SM, there is one Higgs doublet and a spin-0 particle: the Higgs boson (H).

It can be produced at colliders:

Its decays are well known:

Why hasn’t it been discovered yet?
We need higher energy and higher luminosity!
Branching Fractions of the Higgs Boson

Standard Model

Branching Fraction of $H^0$

$M_H$ (GeV)

$10^0$

$10^{-2}$

$10^{-4}$

$10^{-6}$

$WW$

$ZZ$

$t\bar{t}$

$b\bar{b}$

$\mu\bar{\mu}$

$\gamma\gamma$
The Search for the SM Higgs boson

- Mass limit from LEP 2
  With a CM energy up to $\sqrt{s} = 209$ GeV and $L = 100$ pb$^{-1}$ per experiment, a stringent mass limit for the Higgs boson at 95% C.L. is $M_H > 114$ GeV/c$^2$
Discovery potential of hadron colliders

- The Tevatron Run II will be able to discover a SM Higgs boson up to 190 GeV with 30 fb\(^{-1}\), or it will exclude the Higgs boson at 95% C.L. with 10 fb\(^{-1}\).
- The LHC will be able to observe a SM Higgs boson with a mass up to approximately 1 TeV.

Tevatron SM Higgs Combination

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>Limit/SM Exp.</th>
<th>Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>115</td>
<td>7.6</td>
<td>10.4</td>
</tr>
<tr>
<td>130</td>
<td>10.1</td>
<td>10.6</td>
</tr>
<tr>
<td>160</td>
<td>5.0</td>
<td>3.9</td>
</tr>
<tr>
<td>180</td>
<td>7.5</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Note: the combined result is essentially equivalent to one experiment with 1.3 fb$^{-1}$, since both experiments have “complementary” statistics at low and high mass. We are indeed already close to the sensitivity required to exclude or “evidence” the higgs at the Tevatron.

Gregorio Bernardi, ICHEP06, Moscow
Implications of Electroweak Precision Data for Higgs Mass with New $m_t$

M.W. Grunewald (2003); The DØ Collaboration (2004)
$m_{\text{top}} = 173.5 \pm 2.7 - 2.6\text{(stat)} \pm 3.0\text{(syst)} \text{ GeV/c}^2$

The CDF Collaboration (2005).
$m_{\text{top}} = 171.4 \pm 1.2 \pm 1.8 \text{ GeV/c}^2$

The CDF and the D0 Collaborations, hep-ex/0608032.
Problems in the SM Higgs Sector

Requiring unitarity, we must have $M_H \leq 1$ TeV. If $M_H \geq 1$ TeV, WW scattering will become strong. Quadratic divergence: $M_H$ naturally of order $M_{\text{Planck}}$.

One good way out:
A low energy fermion-boson supersymmetry.
The Minimal Supersymmetric Model

In the minimal supersymmetric standard mode (MSSM), there are two Higgs doublets with vacuum expectation value (VEVs) $v_1$ and $v_2$, and five Higgs bosons: two scalars $H^0$ and $h^0$, one pseudoscalar $A^0$, and a pair of singly charged Higgs bosons $H^\pm$.

At the tree level, $m_h \leq M_Z \ 91 \text{ GeV} < m_H$, with radiative corrections, $m_h$ can be in the range $125 \text{ GeV} \leq m_h \leq 135 \text{ GeV}$.

There are only two free parameters in the Higgs sector, often chosen to be $m_A$ and $\tan \beta \equiv v_2/v_1$. 
Mass limit from LEP 2

There are two complementary processes:

\[ e^+e^- \rightarrow Z h^0 \propto \sin^2(\beta - \alpha) \]
and

\[ e^+e^- \rightarrow h^0 A^0 \propto \cos^2(\beta - \alpha) \]

- With a CM energy up to \( \sqrt{s} = 209 \text{GeV} \) and \( L = 100 \text{ pb}^{-1} \) per experiment, the Higgs mass reach at 95% C.L. is MSSM: \( M_{h,A} > 91 \text{ GeV/c}^2 \)
Conclusions

- The MSSM provides the TeVatron with a real shot at a Higgs discovery
  - Light $h^0$, decent xsec
  - Decays to $b, \tau$
- Null results for $\phi^0$ searches put the squeeze on the MSSM from the large $\tan \beta$ side

Andy Hocker, ICHEP06, Moscow
The Search for New Particles at Hadron Colliders

- We need accelerators: Fermilab Tevatron Collider near Chicago and CERN Large Hadron Collider (LHC) in Geneva.
- We need detectors: D0 and CDF (Tevatron), as well as ATLAS and CMS (LHC).
- We look for $e$, $\mu$, $\gamma$ (photon), jets, and hadrons (mesons or baryons).
- A jet = a quark, an anti-quark, or a gluon.
ATLAS
A Toroidal LHC Apparatus
CMS Collaboration
36 Nations, 159 Institutions, 1940 Scientists (February 2003)

TRIGGER & DATA ACQUISITION
Austria, Finland, France, Greece, Hungary, Italy, Korea, Poland,
Portugal, Switzerland, UK, USA

TRACKER
Austria, Belgium, Finland, France, Germany,
Italy, Japan*, New Zealand, Switzerland, UK, USA

CRYSTAL ECAL
Belarus, China, Croatia, Cyprus, France, Italy, Japan*,
Portugal, Russia, Serbia, Switzerland, UK, USA

PRESHOWER
Armenia, Belarus, Greece, India,
Russia, Taipei, Uzbekistan

RETURN YOKE
Barrel: Czech Rep., Estonia, Germany, Greece, Russia
Endcap: Japan*, USA, Brazil

SUPERCONDUCTING MAGNET
All countries in CMS contribute
to Magnet financing in particular:
Finland, France, Italy, Japan*, Korea, Switzerland, USA

HCAL
Barrel: Bulgaria, India, Spain*, USA
Endcap: Belarus, Bulgaria, Russia, Ukraine
HO: India

FEET
Pakistan
China

MUON CHAMBERS
Barrel: Austria, Bulgaria, China, Germany,
Hungary, Italy, Spain,
Endcap: Belarus, Bulgaria, China,
Korea, Pakistan, Russia, USA

* Only through industrial contracts

Total weight : 12500 T
Overall diameter : 15.0 m
Overall length : 21.5 m
Magnetic field : 4 Tesla
Next projects on the HEP roadmap

- **Large Hadron Collider LHC at CERN**: pp @ 14 TeV
  - LHC will be closed and set up for beam on 1 July 2007
  - First beam in machine: August 2007
  - First collisions expected in November 2007
  - Followed by a short pilot run
  - First physics run in 2008 (starting April/May; a few fb$^{-1}$?)

- **Linear Collider (ILC)**: e+e- @ 0.5-1 TeV
  - Strong world-wide effort to start construction earliest around 2009/2010, if approved and budget established
  - Turn on earliest 2015 (in the best of worlds)
  - Study groups in Europe, Americas and Asia (→World Wide Study)

Quest for the Higgs particle is a major motivation for these new machines
Production of Higgs Bosons

A. Gluon Fusion: $gg \rightarrow \phi^0$

B. Bottom Quark Fusion: $b\bar{b} \rightarrow \phi^0$

- $\sigma( gg \rightarrow \phi^0 b\bar{b})[m_b(M_b)]$
  $\approx 3\sigma( gg \rightarrow \phi^0 b\bar{b})[m_b(M_\phi)], M_\phi = 200$ GeV

- $\sigma( gg \rightarrow \phi^0 b\bar{b}) \approx \sigma( b\bar{b} \rightarrow \phi^0), \mu_F = M_\phi/4$

T. Plehn (2002); F. Maltoni, Z. Sullivan and S. Willenbrock (2003);
B. Plumper, DESY-THESIS-2002-005.
Order Counting for Bottom Quark Fusion
Dicus, Stelzer, Sullivan and Willenbrock (1999)

Leading-order contribution: $b\bar{b} \rightarrow H : \mathcal{O}[\alpha_s^2 \ln^2(M_H/m_b)]$

$\mathcal{O}(\alpha_s)$ correction:
(1) $b\bar{b} \rightarrow H$ with virtual gluon, and
(2) $b\bar{b} \rightarrow Hg$: soft, hard/collinear, and hard/non-collinear

$\mathcal{O}[1/\ln(M_H/m_b)]$ correction: $bg \rightarrow bH$

$\mathcal{O}[1/\ln^2(M_H/m_b)]$ corrections: $gg \rightarrow b\bar{b}H$

Next-to-leading order (NLO) correction = $\mathcal{O}(\alpha_s)$ correction + $\mathcal{O}[1/\ln(M_H/m_b)]$ correction.
The Higgs Pseudoscalar \( (A^0) \)
• $A/H \rightarrow \tau\tau$
• $A/H \rightarrow \mu\mu$
• $A/H \rightarrow bb/\mu\mu$ in $bb H/A$
• $A, H \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4l + E_T^{miss}$
• $A, H$ in cascade decays of sparticles

Albert De Roeck, CERN
SUSY 2005
\[ B(A^0 \text{ to } X_2 \ X_2) \]

\[ \sim \tan(b) = 3, \]
\[ M_A = 336 \text{ GeV}, \ M_H = 343 \text{ GeV}, \ M_X = 117 \text{ GeV} \]

\[ \sim A^0 \text{ to } b \ bB \quad 0.095 \]
\[ \sim A^0 \text{ to } X_2 \ X_2 \quad 0.165 \]

\[ \sim \tan(b) = 20, \]
\[ M_A = 292.8 \text{ GeV}, \ M_H = 294.7 \text{ GeV}, \ M_X = 138 \text{ GeV} \]

\[ \sim A^0 \text{ to } b \ bB \quad 0.775 \]
\[ \sim A^0 \text{ to } X_2 \ X_2 \quad 0.030 \]
Discovering the Higgs Bosons with Muons

• The $A^0$ and the $H^0$ might be observable in a large region of parameter space with $\tan\beta \geq 10$.

• This discovery channel of $\mu^+\mu^-$ will allow precise reconstruction for the Higgs boson masses.

• Kao and Stepanov (1995);
Barger and Kao (1998);
Cross Section in the MSSM

$\sqrt{s} = 14$ TeV
$m_t = 175$ GeV

$\tan \beta = 30$
$\tan \beta = 3$
$\tan \beta = 1$

$M_A$ (GeV) vs. $\sigma(pp \rightarrow \phi \rightarrow \mu^+ \mu^- + X)$ (fb)
Minimal Supersymmetry

MSSM

(a) \( \tan \beta = 15, \mu = 1 \text{ TeV} \)
(b) \( \tan \beta = 40, \mu = 1 \text{ TeV} \)
(c) \( \mu = 1 \text{ TeV} \)
(d) \( \mu = 300 \text{ GeV} \)
Discovering Higgs Bosons with Muons and a Bottom Quark

The Physics Backgrounds

• For the associated final state of $b\phi^0 \rightarrow b\mu^+\mu^-$, the dominant physics background comes from $pp \rightarrow b\mu^+\mu^- + X$, and $pp \rightarrow b\bar{b} W^+W^- \rightarrow b\bar{b} \mu^+\mu^- + E_T$

• Additional contributions come from the production of $j\mu^+\mu^-$, $j = g, u, d, s, \text{and } c$.

• We take the $b$ tagging efficiency to be $\varepsilon_b = 0.6$ (LL = 30 fb$^{-1}$) or 0.5 (HL = 300 fb$^{-1}$), $\varepsilon_c = 0.1 = \text{probability of } c \text{ misidentified as } b$, $\varepsilon_j = 0.01 = \text{probability of jets mistagged as } b$.

The Acceptance Cuts

We have applied realistic acceptance cuts proposed for each event at the LHC as follows.

• (a) We require 2 isolated muons with $p_T(\mu) > 20$ GeV, and $|\eta(\mu)| < 2.5$.

• (b) All jets are required to have $p_T(j) > 15$ GeV (LL) or 30 GeV (HL) and $|\eta(j)| < 2.5$.

• (c) To reduce the background from $b\bar{b}WW$ ($t\bar{t}$), we require $E_T < 20$ GeV (LL) or 40 GeV (HL).
$\sqrt{s} = 14$ TeV

(a) $L = 30$ fb$^{-1}$  (b) $L = 300$ fb$^{-1}$

$\sigma (pp \rightarrow b\mu^+\mu^- + X)$(fb)

$M_A$ (GeV)

The Discovery Potential

• To study the discovery potential of
  \[ pp \rightarrow b \phi^0 \rightarrow b \mu^+ \mu^- + X \]
  we calculate the SM background from
  \[ pp \rightarrow b \mu^+ \mu^- + X \]
  and
  \[ pp \rightarrow b \bar{b} W^+ W^- \rightarrow b \bar{b} \mu^+ \mu^- + X \]
in the mass window of \( m_\phi \pm \Delta M_{\mu\mu} \).
• \( \Delta M_{\mu\mu} = 1.64 \left[ (\Gamma_\phi/2.36)^2 + \sigma_m^2 \right]^{1/2} \),
• \( \Gamma_\phi \) is the width of the Higgs boson, and
• \( \sigma_m \) = the muon mass resolution \( \equiv 0.02 \, m_\phi \).
Discovery Potential at the LHC

MSSM, $M_{\text{SUSY}} = 1$ TeV

(a) $L = 30 \, \text{fb}^{-1}$
(b) $L = 300 \, \text{fb}^{-1}$

![Graphs showing discovery potential at the LHC with mass scale and $\tan\beta$ on the axes.](image-url)
Summary for Higgs Decay into Muons

- The discovery channel of $b\phi^0 \rightarrow b\mu^+\mu^-$ offers great promise to discover the $A^0$ and the $H^0$ at the LHC for $\tan\beta > 10$, $m_A < 650$ GeV with $L = 30$ fb$^{-1}$.
- A higher luminosity of 300 fb$^{-1}$ can improve the discovery reach in $m_A$ up to $m_A = 800$ GeV.
- The $b\phi^0$ channel greatly improves the discovery potential beyond the reach of the inclusive channel $pp \rightarrow \phi^0 \rightarrow \mu^+\mu^- + X$.
- This discovery channel might provide good opportunities to measure important parameters such as the Higgs masses, $\tan\beta$, and Higgs couplings with bottom quarks and leptons.
The Minimal Supergravity Model

In the minimal supergravity unified model (mSUGRA), it is assumed that SUSY is broken in a hidden sector with SUSY breaking communicated to the observable sector through gravitational interactions, leading to a common scalar mass ($m_0$), a common gaugino mass ($m_{1/2}$), a common trilinear coupling ($A_0$), and a bilinear coupling ($B_0$) at the grand unified scale ($M_{GUT}$).

We often choose $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, and $\text{sign}(\mu)$ as the 5 free parameters.

The masses and couplings of SUSY particles are evaluated with renormalization group equations.
Barger and Kao (1998)
Higgs bosons of minimal supergravity

In addition to $m_0$ and $m_{1/2}$, $\tan\beta$ is a very important parameter:

• an increase in $\tan\beta$ leads to a larger $m_h$ but a reduction in $m_A$ and $m_H$;

• for $\tan\beta \sim 2$, $m_A$ is usually large and the cross section of a Higgs signal for $H^0$ or $A^0$ is often much smaller than that of the background;

• for $\tan\beta \geq 35$, the cross section of the Higgs signal is greatly enhanced and can become slightly larger than the background.
Minimal Supergravity Model

(a) $\tan \beta = 20$  
(b) $\tan \beta = 30$

Green: $L = 30$ fb$^{-1}$ 
Magenta: $L = 300$ fb$^{-1}$

(c) $\tan \beta = 40$  
(d) $\tan \beta = 50$
$B_s \rightarrow \mu^+ \mu^-$

- This rare decay has a small branching fraction in the Standard Model
  \[ B(B_s \rightarrow \mu^+ \mu^-) = 3.4 \times 10^{-9} \]

- The current experimental upper limit from CDF and D0 is
  \[ B(B_s \rightarrow \mu^+ \mu^-) < 1.5 \times 10^{-7} \]
$B_s \rightarrow \mu\mu$ and SUSY

$$B(B_s \rightarrow \mu^+\mu^-) \sim 5 \times 10^{-7} \left(\frac{\tan \beta}{50}\right)^6 \left(\frac{300 \text{GeV}}{M_A}\right)^4$$

The discovery region of a neutral Higgs boson through $pp \rightarrow bH \rightarrow b\mu\mu\mu$ at LHC and the discovery region of $B_s \rightarrow \mu\mu\mu$ at Tevatron and LHC overlap.


Y Okada (ICHEP 2006)
Comparison with the charged Higgs boson production at LHC

- The parameter region covered by B decays and the charged Higgs production overlaps.
- If both experiments find positive effects, we can perform Universality Test of the charged Higgs couplings.

B-\to\tau\nu: \ H-b-u \ coupling
B-\to D\tau\nu: \ H-b-c \ coupling
gb-\to tH: \ H-b-t \ coupling

SUSY loop vertex correction can break the universality.

Belle B-\to\tau\nu: \text{excluded region (95.5\%CL)}
State-of-the-art (before ICHEP06)

- All decay channels beyond the reach of experiments:

<table>
<thead>
<tr>
<th>Mode</th>
<th>$B_{s}^{0} \rightarrow \mu^{+}\mu^{-}$</th>
<th>$B_{d}^{0} \rightarrow \mu^{+}\mu^{-}$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM Expect.</td>
<td>$3.5 \times 10^{-9}$</td>
<td>$1.0 \times 10^{-10}$</td>
<td>Buras, 2003</td>
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<tr>
<td>CLEO</td>
<td>-</td>
<td>$6.1 \times 10^{-7}$</td>
<td>PRD62, 091102</td>
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<td>PRD68, 111101</td>
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<td>PRL93, 032001</td>
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<td>D0</td>
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<td>-</td>
<td>PRL94, 071802</td>
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<td>PRL94, 221803</td>
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<td>$0.39 \times 10^{-7}$</td>
<td>PRL95, 221805 + Err.</td>
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<tr>
<td>CDF</td>
<td>$0.8 \times 10^{-7}$</td>
<td>$0.23 \times 10^{-7}$</td>
<td>CDF public note 8176</td>
</tr>
</tbody>
</table>

- $B$-factories search also for
  - $B_{s}^{0} \rightarrow e^{+}e^{-}$
  - $B_{s}^{0} \rightarrow e^{\pm}\mu^{\mp}$

- SM branching ratio is very low:
  - $b\bar{b}$ cross section at LHC $\sim 10\times$ larger
    than at Tevatron
  - Events can be triggered at high luminosity

Urs Langenegger
Study of $B_{s}^{0} \rightarrow \mu^{+}\mu^{-}$ in CMS (2006/07/28, XXXIII ICHEP 2006)
Conclusions

- First CMS update on search for $B^0_s \rightarrow \mu^+\mu^-$ since 1999
  - Full reconstruction with pileup for $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$

- Expected upper limit in 10 fb$^{-1}$: $\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) \leq 1.4 \times 10^{-8}$
  - study limited by size of background MC sample
  - good mass resolution

- Outlook
  - include rare $B$ decays
  - full analysis: likelihood selection and normalization sample

(from hep-ph/0310042)
Expected Limit x 10^8 (90% CL)

CDF Projection
BR(B_s \rightarrow \mu^+\mu^-)

New analysis (significant improvement compared to PRL 93 032001 (2004))

Current limit (CDF 365pb^{-1})

Projection based on CDF PRL 93 032001 (2004)
\[ B_s \rightarrow \mu^+ \mu^- \text{ in the MSSM} \]

We consider SUSY contributions from loop diagrams involving

\sim \text{ the charged Higgs boson,}
\sim \text{ the charginos,}
\sim \text{ the neutrinos, and}
\sim \text{ the gluino.}
Feynman Diagrams

(a) $\mu \phi^0 \tilde{d}_i \tilde{d}_j \mu$

(b) $\mu \phi^0 \tilde{u}_i \tilde{u}_j \mu$

(c) $\mu \phi^0 u_i u_j \mu$

(d) $\mu \phi^0 \tilde{d}_i \tilde{d}_j \mu$

(b) $\mu \phi^0 \tilde{u}_i \tilde{u}_j \mu$

(c) $\mu \phi^0 u_i u_j \mu$

(d) $\mu \phi^0 \tilde{d}_i \tilde{d}_j \mu$
Recent Studies

~ Arnowitt, Dutta, Kamon and Tanaka (2002); Bobeth, Ewerth, Kruger and Urban (2002); Buras, Chankowski, Rosiek and Slawianowska (2002); Kane, Kolda and Lennon (2003; Dedes and Pilaftsis (2002); Dedes (2003); Dedes and Huffma (2004).
~ Ellis, Olive and Spanos (2005); Ellis, Olive, Santoso and Spanos (2006).
Branching Fraction versus $m_A$

MSSM

(a) $M_{\text{SUSY}} = 350$ GeV  (b) $M_{\text{SUSY}} = 1000$ GeV

$B(B_s \rightarrow \mu^+ \mu^-)$

$\tan\beta = 50$

$\tan\beta = 20$

$\tan\beta = 40$

$\tan\beta = 30$

$M_A$ (GeV)

$M_A$ (GeV)
Branching Fraction versus $\tan(\beta)$

MSSM

(a) $M_{\text{SUSY}} = 350$ GeV  (b) $M_{\text{SUSY}} = 1000$ GeV
Minimal Supersymmetric Model

MSSM

$M_{SUSSY} = 350$ GeV, $\mu > 0$

$M_{SUSSY} = 1000$ GeV, $\mu > 0$
B_s to mu mu
versus
A^0,H^0 to tau tau

Minimal Supergravity Model

mSUGRA

\[
\begin{align*}
\text{m}_{1/2} & < 103.5 \text{ GeV} \\
\tan \beta & = 20, \ A_0 = 0, \ \mu > 0 \\
\text{m}_{1/2} & < 103.5 \text{ GeV} \\
\tan \beta & = 30, \ A_0 = 0, \ \mu > 0 \\
\tan \beta & = 40, \ A_0 = 0, \ \mu > 0 \\
\tan \beta & = 50, \ A_0 = 0, \ \mu > 0
\end{align*}
\]

\[5 \times 10^{-9} \text{ fb}^{-1}, \ 3 \times 10^{-8} \text{ fb}^{-1}, \ 1.5 \times 10^{-7} \text{ fb}^{-1}\]
Non-universal Supergravity Models

Supergravity models with non-universal Higgs boson masses (NUHM SUGRA) give more interesting rates.

The Higgs masses at $M_{\text{GUT}}$ are chosen to be
$$m_{H_i}^2(\text{GUT}) = (1 + \delta_i)m_0^2, \ i = 1, 2.$$

In our NUHM SUGRA cases, $m_A$ and $m_H$ are smaller than those in the mSUGRA model for the same values of $m_0$ and $m_{1/2}$.

Consequently, both
$$b\phi^0 \rightarrow b\mu^+\mu^- \ and \ B_s \rightarrow \mu^+\mu^-$$
will be able to cover regions of the parameter space with larger values of $m_0$ and $m_{1/2}$. 
NUHM SUGRA Case I

\( \tan \beta = 20, \delta_1 = -0.5, \delta_2 = 0 \)

\( m_{1/2} < 103.5 \text{ GeV} \)

\( \chi_1^0 \) not LSP

\( m_0 (\text{GeV}) \)

\( m_{1/2} (\text{GeV}) \)

\( \tan \beta = 30, \delta_1 = -0.5, \delta_2 = 0 \)

\( m_{1/2} < 103.5 \text{ GeV} \)

\( \chi_1^0 \) not LSP

\( m_0 (\text{GeV}) \)

\( m_{1/2} (\text{GeV}) \)

\( \tan \beta = 40, \delta_1 = -0.5, \delta_2 = 0 \)

\( m_{1/2} < 103.5 \text{ GeV} \)

\( \chi_1^0 \) not LSP

\( m_0 (\text{GeV}) \)

\( m_{1/2} (\text{GeV}) \)

\( \tan \beta = 50, \delta_1 = -0.5, \delta_2 = 0 \)

\( m_{1/2} < 103.5 \text{ GeV} \)

\( \chi_1^0 \) not LSP

\( m_0 (\text{GeV}) \)

\( m_{1/2} (\text{GeV}) \)
NUHM SUGRA Case II

\[ \tan\beta = 20, \delta_1 = 0, \delta_2 = 0.5 \]

\[ \tan\beta = 30, \delta_1 = 0, \delta_2 = 0.5 \]

\[ \tan\beta = 40, \delta_1 = 0, \delta_2 = 0.5 \]

\[ \tan\beta = 50, \delta_1 = 0, \delta_2 = 0.5 \]

\[ \chi_1^0 \text{ not LSP} \]

\[ \chi_1^0 \text{ not LSP} \]

\[ \chi_1^0 \text{ not LSP} \]

\[ \chi_1^0 \text{ not LSP} \]
Summary

(a) The contours for $B(B_s \rightarrow \mu^+\mu^-) = 1 \times 10^{-8}$ in the parameter space are very close to the $5\sigma$ contours for $pp \rightarrow b\phi^0 \rightarrow b\mu^+\mu^- + X$, at the LHC with $L = 30 \text{ fb}^{-1}$.

(b) The regions covered by $B(B_s \rightarrow \mu^+\mu^-) \geq 5 \times 10^{-9}$ and the discovery region for $b\phi^0 \rightarrow b\mu^+\mu^- + X$ with $300 \text{ fb}^{-1}$ are complementary in the mSUGRA parameter space.

(c) In SUGRA models with nonuniversal Higgs masses, a discovery for $B(B_s \rightarrow \mu^+\mu^-) \simeq 5 \times 10^{-9}$ at the LHC will cover regions of the parameter space beyond the direct search for $pp \rightarrow b\phi^0 \rightarrow b\mu^+\mu^- + X$, with $L = 300 \text{ fb}^{-1}$. 