Exclusive rare B decays:

\[ B^0_d \rightarrow \mu^+\mu^- \] and \[ B_s \rightarrow \mu^+\mu^- \]

Gaia Lanfranchi
LNF-INFN
on behalf of the LHCb Collaboration

*Flavour and the forth family, Durham 13-16 September 2011*
Outline

• (Brief) theoretical introduction
• Experimental status
• LHCb-CMS analysis strategies
• Results
• $B_s \rightarrow \mu \mu$ and global fits
• Conclusions & outlook
The LHCb hunt for non-SM Higgs(es)

B_{(d,s)} \rightarrow \mu\mu \text{ is the best way for LHCb to constrain the parameters of the extended Higgs sector in MSSM, fully complementary to direct searches}

\[ BR(B_q \rightarrow \ell^+\ell^-) \approx \frac{G_F^2\alpha^2 M_{B_q}^3 f_{B_q}^2 T_B}{64\pi^3 \sin^4 \theta_W} \left| V_{tb} V_{ts}^* \right|^2 \sqrt{1 - \frac{4m_l^2}{M_{B_q}^2}} \]

\[ \left\{ M_{B_q}^2 \left( 1 - \frac{4m_l^2}{M_{B_q}^2} \right) c_s^2 + \left[ M_{B_q} c_P + \frac{2m_l}{M_{B_q}} (c_A - c'_A) \right]^2 \right\} . \]

Double suppressed decay: FCNC process and helicity suppressed: \rightarrow \text{very small in the Standard Model but very well predicted:}

\[ B_s \rightarrow \mu^+\mu^- = (3.2\pm0.2) \times 10^{-9} \]  \[ B_d \rightarrow \mu^+\mu^- = (1.0\pm0.1) \times 10^{-10} \]

Buras et al., arXiv:1007.5291 and references therein
The LHCb hunt for non-SM Higgs(es)

$B_{(d,s)} \rightarrow \mu \mu$ is the best way for LHCb to constrain the parameters of the extended Higgs sector in MSSM, fully complementary to direct searches

$$\begin{align*}
BR(B_q \rightarrow l^+l^-) & \approx \frac{G_F^2 \alpha^2 M_{B_q}^3 f_{B_q}^2 T_F}{64 \pi^3 \sin^4 \theta_W} |V_{tb} V_{ts}^*|^2 \sqrt{1 - \frac{4m_l^2}{M_{B_q}^2}} \\
\left\{M_{B_q}^2 \left(1 - \frac{4m_l^2}{M_{B_q}^2}\right) c_s^2 + \left[M_{B_q} c_P + \frac{2m_l}{M_{B_q}} (c_A - c'_A)\right]^2 \right\}.
\end{align*}$$

Double suppressed decay: FCNC process and helicity suppressed:
→ very small in the Standard Model but very well predicted:

$B_s \rightarrow \mu^+\mu^- = (3.2 \pm 0.2) \times 10^{-9}$

$B_d \rightarrow \mu^+\mu^- = (1.0 \pm 0.1) \times 10^{-10}$

Buras et al., arXiv:1007.5291 and references therein

Helicity suppression:
all relevant SM diagrams contribute to $C_A$
as the diagram with Higgs exchange is fully negligible $\sim (m_b/m_W)^2$
The LHCb hunt for non-SM Higgs(es)

\( B_{(d,s)} \to \mu\mu \) is the best way for LHCb to constrain the parameters of the extended Higgs sector in MSSM, fully complementary to direct searches.

\[
\begin{align*}
BR(B_q \to l^+l^-) &\approx \frac{G_F^2 |\alpha|^2 M_{B_q}^3 f_{B_q}^2 T_B}{64 \pi^3 \sin^4 \theta_W} \left[ |V_{tb} V_{ts}|^2 \sqrt{1 - \frac{4m_l^2}{M_{B_q}^2}} \right], \\
&\left\{ M_{B_q}^2 \left( 1 - \frac{4m_l^2}{M_{B_q}^2} \right) c_s^2 + \left[ M_{B_q} c_P + \frac{2m_l}{M_{B_q}} c_A - c_A' \right] \right\}^2.
\end{align*}
\]

Double suppressed decay: **FCNC process and helicity suppressed:**

\( \Rightarrow \) very small in the Standard Model but very well predicted:

\[
\begin{align*}
B_s \to \mu^+\mu^- &= (3.2\pm0.2) \times 10^{-9} \\
B_d \to \mu^+\mu^- &= (1.0\pm0.1) \times 10^{-10}
\end{align*}
\]

In SM \( BR(B_{s(d)} \to l^+l^-) \) is proportional to \( |V_{ts(d)}|^2 \):

1. \( BR(B_d \to l^+l^-) \sim 30 \) times lower than the \( B_s \to l^+l^- \)
2. The ratio of \( BR(B_s \to ll)/BR(B_d \to ll) = |V_{ts}|^2/|V_{td}|^2 \) in SM and MFV models
The LHCb hunt for non-SM Higgs(es)

\( B_{(d,s)} \rightarrow \mu \mu \) is the best way for LHCb to constrain the parameters of the extended Higgs sector in MSSM, fully complementary to direct searches.

\[
\text{BR}(B_q \rightarrow \ell^+\ell^-) \approx \frac{G_F^2 \alpha^2 M_{B_q}^3 f_{B_q}^2 T_{B_q} |V_{tb} V_{tq}^*|^2}{64 \pi^3 \sin^4 \theta_W} \sqrt{1 - \frac{4m_{l}^2}{M_{B_q}^2}} \left\{ M_{B_q}^2 \left( 1 - \frac{4m_{l}^2}{M_{B_q}^2} \right) c_S^2 + \left[ M_{B_q} c_P + \frac{2m_{l}}{M_{B_q}} (c_A - c'_A) \right]^2 \right\}.
\]

Double suppressed decay: **FCNC process and helicity suppressed**:  
\( \rightarrow \) very small in the Standard Model but very well predicted:

\[
B_s \rightarrow \mu^+\mu^- = (3.2 \pm 0.2) \times 10^{-9} \quad \text{and} \quad B_d \rightarrow \mu^+\mu^- = (1.0 \pm 0.1) \times 10^{-10}
\]

\( \rightarrow \text{sensitive to New Physics} \) contributions in the scalar/pseudo-scalar sector:

\[
(c_{S,P}^{MSSM})^2 \propto \left( \frac{m_b m_\mu \tan^3 \beta}{M_A^2} \right)^2
\]

MSSM, large \( \tan \beta \) approximation
# Experimental results (before summer 2011)

Published $B_s \to \mu\mu$ limits @ 95% CL

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Data set</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>3.7 fb$^{-1}$</td>
<td>$4.3 \times 10^{-8}$</td>
</tr>
<tr>
<td>D0</td>
<td>6.1 fb$^{-1}$</td>
<td>$5.1 \times 10^{-8}$</td>
</tr>
<tr>
<td>LHCb</td>
<td>0.036 fb$^{-1}$</td>
<td>$5.6 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

LHCb equivalent to CDF with ~100 times less luminosity
Experimental results (before summer 2011)

Published $B_s \rightarrow \mu\mu$ limits @ 95% CL

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Data set</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>3.7 fb$^{-1}$</td>
<td>4.3 x 10$^{-8}$</td>
</tr>
<tr>
<td>D0</td>
<td>6.1 fb$^{-1}$</td>
<td>5.1 x 10$^{-8}$</td>
</tr>
<tr>
<td>LHCb</td>
<td>0.036 fb$^{-1}$</td>
<td>5.6 x 10$^{-8}$</td>
</tr>
</tbody>
</table>

But also an anomaly:
long-staying (since La Thuile)
expected-only limit from CDF:
$\text{BR}(B_s \rightarrow \mu\mu) < 2 \times 10^{-8}$ @ 95% CL
July 12th, 2011:
CDF sends to archive the following paper:

Search for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ Decays with CDF II

A search has been performed for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ decays using 7 fb$^{-1}$ of integrated luminosity collected by the CDF II detector at the Fermilab Tevatron collider. The observed number of $B^0$ candidates is consistent with background-only expectations and yields an upper limit on the branching fraction of $\mathcal{B}(B^0 \to \mu^+\mu^-) < 6.0 \times 10^{-9}$ at 95% confidence level. We observe an excess of $B_s^0$ candidates. The probability that the background processes alone could produce such an excess or larger is 0.27%. The probability that the combination of background and the expected standard model rate of $B_s^0 \to \mu^+\mu^-$ could produce such an excess or larger is 1.9%. These data are used to determine $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8}$ and provide an upper limit of $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 4.0 \times 10^{-8}$ at 95% confidence level.

arXiv: 1107.2304 [hep-ex]
CDF result based on:
1) double sample size (3.7 fb\(^{-1}\) → 7 fb\(^{-1}\))
2) +20% acceptance for muons
3) improved Neural Network

\[ M_{\mu\mu} \text{ distribution in Bs search window for different NN bins} \]

2.8 \(\sigma\) assuming bkg-only hypothesis
1.9% compatibility with bkg+SM hypothesis

\[ 0.46 \times 10^{-8} < \text{BR} < 3.9 \times 10^{-8} @ 90\% \text{ CL (BR}=1.8^{+1.1}_{-0.9}) \times 10^{-8} \]
Given the CDF central value, LHCb should see ~20 events in the Bs mass window (a mountain)!
…but on July 12\textsuperscript{th} we had still the search window blinded (the unblinding of the result for EPS was foreseen only few days later)
Given the CDF central value, LHCb should see ~20 events in the Bs mass window (a mountain)!

…but on July 12\textsuperscript{th} we had still the search window blinded (the unblinding of the result for EPS was foreseen only few days later)

we managed to stick on the plans in an ordered way
Given the CDF central value, LHCb should see ~20 events in the Bs mass window (a mountain)!

…but on July 12th we had still the search window blinded (the unblinding of the result for EPS was foreseen only few days later)

we managed to stick on the plans in an ordered way (almost)..
Given the CDF central value, LHCb should see ~20 events in the Bs mass window (a mountain)!

…but on July 12th we had still the search window blinded (the unblinding of the result for EPS was foreseen only few days later)

we managed to stick on the plans in an ordered way (almost)..

…we performed the final checks and three days later we opened the window in front our internal referees.. July 15th, 5 days to EPS….
Experimental parameters for the search of $B_{s,d} \rightarrow \mu \mu$

- Huge cross section:
  \[ \text{LHC } \sigma (pp \rightarrow \text{bbX}) @ 7 \text{ TeV} \sim 300 \mu b \ (\text{Tevatron} \sim 100 \mu b) \]

- Large acceptance (bb are produced forward/backward):
  \[ \text{LHCb acceptance } 1.9 < \eta < 4.9 \ (\text{CDF: } |\eta| < 1 \ ; \ D0: \ |\eta| < 2, \ CMS: \ |\eta| < 2.4) \]
  \[ \Rightarrow \varepsilon \text{(acceptance) in LHCb for } B_{sd} \rightarrow \mu \mu \sim 10\% \ (\text{CDF} \sim 1\%) \]

- Large boost:
  \[ \Rightarrow \text{average flight distance of } B \text{ mesons } @ \text{LHC} \sim 1 \text{ cm} \ (\text{Tevatron: } 2 \text{ mm}) \]
  
  ... LHCb has a huge amount of very displaced b’s…….
.... But in a harsh environment!

- $\sigma(pp, \text{ inelastic}) \@ \sqrt{s}=7 \text{ TeV} \sim 60 \text{ mb}$
- 60 tracks per event in ‘high’-pileup conditions ($\sim$2 pp interactions Xing)
- only 1/200 event contains a $b$ quark, and we are looking for $BR \sim 10^{-9}$

LHCb expects 3.4 (0.32) $B_S (B_d) \rightarrow \mu\mu$ events triggered and reconstructed in $\sim 300 \text{ pb}^{-1}$ if $BR = BR(SM)$
Key ingredients for $B_{s,d} \rightarrow \mu\mu$

1) Efficient trigger:
   - to identify leptonic final states with low-pT thresholds

2) Background reduction:
   - Very good mass resolution:
     $\rightarrow$ sigma(MB$_{s,d}$) $\sim$ 26 MeV  [CDF: 25 MeV, CMS: 40 $\rightarrow$ >80 MeV]
   - Good particle identification: $\varepsilon(\mu \rightarrow \mu)$ $\sim$ 98% for $\varepsilon(h \rightarrow \mu)$ < 1% for p>10 GeV/c
   - Excellent vertex & IP resolution to separate signals from background:
     $\sigma$(IP)$\sim$ 25 $\mu$m @ p$_T$=2 GeV/c (the best at LHC)
LHCb analysis strategy

• **Soft selection:**
  - reduces the dataset to a manageable level

• **Discrimination between S and B via Multi Variate Discriminant variable (Boosted Decision Tree) and Invariant Mass (IM)**
  - events in the sensitive region are classified in bins of a 2D plane
  Invariant Mass and BDT variables, expected background from the fit of the mass sidebands.

• **Normalization:**
  Convert the signal PDFs into a number of expected signal events by normalizing to channels of known BR (this get rid of L and \(\sigma(bb)\)):
  \[\rightarrow \text{use } B^+ \rightarrow J/\psi K^+, \; B_s \rightarrow J/\psi \phi, \; B_d \rightarrow K \pi\]
  \[\rightarrow \text{use } fd/fs \text{ combined LHCb result: } fs/fd = 0.267^{+0.021}_{-0.020}\]

• **Extraction of the limit:**
  - assign to each observed event a probability to be S+B or B-only as a function of the \(\text{BR}(B_{s,d} \rightarrow \mu\mu)\) value; exclude (observe) the assumed BR value at a given confidence level using the **CLs binned method**.
Analysis performed in the 2D plane: Invariant mass vs BDT

BDT distributions for signal and background

M(\mu\mu) vs BDT plane
4 BDT bins
6 mass bins

Search windows (M(Bs,d) ± 60 MeV)
LHCb: background in the search windows from fit to data sidebands
(…..no peak, clearly….)

Bd mass window

Bs mass window
LHCb result in the $B_d$ mass window with 300 pb$^{-1}$ (preliminary)

<table>
<thead>
<tr>
<th>BDT range</th>
<th>Exp.combinatorial</th>
<th>Exp. MisID</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25&lt;BDT</td>
<td>3175 ± 72</td>
<td>0.6± 0.1</td>
<td>3025</td>
</tr>
<tr>
<td>0.5&lt;BDT</td>
<td>26.6 ± 2.5</td>
<td>0.6± 0.1</td>
<td>31</td>
</tr>
<tr>
<td>0.75&lt;BDT</td>
<td>3.1 ± 0.8</td>
<td>0.6± 0.1</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>0.7 ± 0.4</td>
<td>0.6± 0.1</td>
<td>4</td>
</tr>
</tbody>
</table>
LHCb preliminary limit for $\text{BR}(B_d \rightarrow \mu\mu)$ with 300 pb$^{-1}$ (world best)

![Graph showing CLs vs $B(B^0 \rightarrow \mu^+\mu^-)$ at 90% and 95% CL]

<table>
<thead>
<tr>
<th>$B^0 \rightarrow \mu^+\mu^-$</th>
<th>at 90% CL</th>
<th>at 95% CL</th>
<th>$\text{CL}_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>expected limit (bkg only hypothesis)</td>
<td>$2.4 \times 10^{-9}$</td>
<td>$3.1 \times 10^{-9}$</td>
<td></td>
</tr>
<tr>
<td>observed limit</td>
<td>$4.2 \times 10^{-9}$</td>
<td>$5.2 \times 10^{-9}$</td>
<td>$0.79$</td>
</tr>
</tbody>
</table>

CDF: $6.0 \times 10^{-9}$ @ 95% CL
LHCb result in the $B_s$ mass window with 300 pb$^{-1}$
(preliminary)

<table>
<thead>
<tr>
<th></th>
<th>BDT&lt;0.25</th>
<th>0.25&lt;BDT&lt;0.5</th>
<th>0.5&lt;BDT&lt;0.75</th>
<th>0.75&lt;BDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.combinatorial</td>
<td>2968 ± 69</td>
<td>25 ± 2.5</td>
<td>2.99 ± 0.89</td>
<td>0.66 ± 0.40</td>
</tr>
<tr>
<td>Exp. SM signal</td>
<td>1.26 ± 0.13</td>
<td>0.61 ± 0.06</td>
<td>0.67 ± 0.07</td>
<td>0.72 ± 0.07</td>
</tr>
<tr>
<td>Observed</td>
<td>2872</td>
<td>26</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>
LHCb result in the $B_s$ mass window with 300 pb$^{-1}$ (preliminary)

<table>
<thead>
<tr>
<th>BDT region</th>
<th>Exp. combinatorial</th>
<th>Exp. SM signal</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDT&lt;0.25</td>
<td>2968 ± 69</td>
<td>1.26 ± 0.13</td>
<td>2872</td>
</tr>
<tr>
<td>0.25&lt;BDT&lt;0.5</td>
<td>25 ± 2.5</td>
<td>0.61 ± 0.06</td>
<td>26</td>
</tr>
<tr>
<td>0.5&lt;BDT&lt;0.75</td>
<td>2.99 ± 0.89</td>
<td>0.67 ± 0.07</td>
<td>3</td>
</tr>
<tr>
<td>0.75&lt;BDT</td>
<td>0.66 ± 0.40</td>
<td>0.72 ± 0.07</td>
<td>2</td>
</tr>
</tbody>
</table>
A $B_s \to \mu\mu$ candidate in the LHCb event display:
LHCb preliminary limit for $\text{BR}(B_s \rightarrow \mu\mu)$ with 300 pb$^{-1}$ (world best)
CMS result for $B_s \to \mu\mu$ search with 1.14 fb$^{-1}$

[arXiv:1107.5834v1, CMS-BPH-11-002]

- Cut based analysis, sample divided in two bins: both muons in barrel ($|\eta| < 1.4$), one $\mu$ in barrel one in endcap ($1.4 < |\eta| < 2.4$).
- Normalization with $B^+ \to J/\psi K$ using $f_d/f_s = 0.282 \pm 0.037$ [pdg]

<table>
<thead>
<tr>
<th></th>
<th>Barrel</th>
<th>Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{signal}}^{\text{exp}}$</td>
<td>0.80 ± 0.16</td>
<td>0.36 ± 0.07</td>
</tr>
<tr>
<td>$N_{\text{exp}}$</td>
<td>0.60 ± 0.35</td>
<td>0.80 ± 0.40</td>
</tr>
<tr>
<td>$N_{\text{bg}}$</td>
<td>0.07 ± 0.02</td>
<td>0.04 ± 0.01</td>
</tr>
<tr>
<td>$N_{\text{peak}}^{\text{exp}}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{\text{obs}}$</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 4: Dimuon invariant mass distributions in the barrel (left) and endcap (right) channels. The signal windows for $B_s^0$ and $B^0$ are indicated by horizontal lines.
CMS result for $B_s \rightarrow \mu \mu$ search with 1.14 fb$^{-1}$

[arXiv:1107.5834v1, CMS-BPH-11-002]

- Cut based analysis, sample divided in two bins: both muons in barrel ($|\eta| < 1.4$), one $\mu$ in barrel one in endcap ($1.4 < |\eta| < 2.4$).
- Normalization with $B^+ \rightarrow J/\psi K$ using $f_d/f_s = 0.282 \pm 0.037$ [pdg]

<table>
<thead>
<tr>
<th></th>
<th>Barrel</th>
<th>Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{signal}}^{\text{exp}}$</td>
<td>$0.80 \pm 0.16$</td>
<td>$0.36 \pm 0.07$</td>
</tr>
<tr>
<td>$N_{\text{exp}}^b$</td>
<td>$0.60 \pm 0.35$</td>
<td>$0.80 \pm 0.40$</td>
</tr>
<tr>
<td>$N_{\text{peak}}^{\text{exp}}$</td>
<td>$0.07 \pm 0.02$</td>
<td>$0.04 \pm 0.01$</td>
</tr>
<tr>
<td>$N_{\text{obs}}$</td>
<td>$2$</td>
<td>$1$</td>
</tr>
</tbody>
</table>

Expected limit at 95% C.L. (including presence of SM signal)

$1.8 \times 10^{-8}$

Observed limit at 95% (90%) C.L.

$1.9 (1.6) \times 10^{-8}$

p-value of bckg only hypothesis

$11\%$
Combination has been performed by LHCb just adding 2 CMS bins (1 for barrel, 1 for endcap):

\[ \text{BR}(B_s \rightarrow \mu \mu) < 1.1 \times 10^{-8} @ 95\% \text{ CL (3.4xSM)} \]
LHCb-CMS combination

Combination has been performed by LHCb just adding 2 CMS bins (1 for barrel, 1 for endcap):

Most probable value \(~4\times10^{-9}\)
BR($B_s \to \mu\mu$) and Global Fits

An example: MasterCode (J. Ellis et al.) (http://www.cern.ch/mastercode) Goal: perform global fits to measured quantities (including direct) and build a $\chi^2$ searches) compare with prediction from a given model (CMSSM, NUMH1, mSugra, etc.)

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{(f_{obs} - f_{fit})^2}{\sigma(f_{SM_i})^2}$$

$$+ \chi^2(b \to s\gamma) + \chi^2(g_\mu - 2) + \chi^2(\Omega h^2) + \chi^2(m_h)$$

$$+ \chi^2(BR(B_s \to \mu\mu)) + \chi^2(LHC) + \chi^2(XENON100)$$

$N$: number of observables studied

$M$: SM parameters: $\Delta \alpha_{\text{had}}, m_t, M_Z$

$C_i$: experimentally measured value (constraint)

$P_i$: MSSM parameter-dependent prediction for the corresponding constraint
Global fits: input data

**EW observables**
(largest impact $M_W$, $A_{e \text{LR}}$, $A_{b \text{FB}}$)

<table>
<thead>
<tr>
<th>Observable</th>
<th>Source Th./Ex.</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_t$ [GeV]</td>
<td>[39]</td>
<td>173.2 ± 0.90</td>
</tr>
<tr>
<td>$\Delta a_{\text{had}}^{(b)} (m_t)$</td>
<td>[38]</td>
<td>0.02749 ± 0.00010</td>
</tr>
<tr>
<td>$M_Z$ [GeV]</td>
<td>[40]</td>
<td>91.1875 ± 0.0021</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>[24] / [40]</td>
<td>$2.4052 ± 0.0023 ± 0.001_{\text{SU}}$</td>
</tr>
<tr>
<td>$\sigma^0_{\text{had}}$ [nb]</td>
<td>[24] / [40]</td>
<td>41.540 ± 0.037</td>
</tr>
<tr>
<td>$R_t$</td>
<td>[24] / [40]</td>
<td>20.767 ± 0.25</td>
</tr>
<tr>
<td>$A_{t}(c)$</td>
<td>[24] / [40]</td>
<td>0.01714 ± 0.00095</td>
</tr>
<tr>
<td>$A_{t}(P_t)$</td>
<td>[24] / [40]</td>
<td>0.1465 ± 0.0032</td>
</tr>
<tr>
<td>$R_b$</td>
<td>[24] / [40]</td>
<td>0.21629 ± 0.00066</td>
</tr>
<tr>
<td>$R_c$</td>
<td>[24] / [40]</td>
<td>0.1721 ± 0.0030</td>
</tr>
<tr>
<td>$A_{b}(b)$</td>
<td>[24] / [40]</td>
<td>0.0092 ± 0.0016</td>
</tr>
<tr>
<td>$A_{b}(c)$</td>
<td>[24] / [40]</td>
<td>0.0707 ± 0.0035</td>
</tr>
<tr>
<td>$A_{c}$</td>
<td>[24] / [40]</td>
<td>0.923 ± 0.020</td>
</tr>
<tr>
<td>$A_{s}$</td>
<td>[24] / [40]</td>
<td>0.670 ± 0.027</td>
</tr>
<tr>
<td>$A_{t}(\text{SLD})$</td>
<td>[24] / [40]</td>
<td>0.1513 ± 0.0021</td>
</tr>
<tr>
<td>$\sin^2\theta_W(Q_{\text{FA}})$</td>
<td>[24] / [40]</td>
<td>0.2324 ± 0.0012</td>
</tr>
<tr>
<td>$M_W$ [GeV]</td>
<td>[24] / [40]</td>
<td>80.399 ± 0.023 ± 0.010_{SU}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observable</th>
<th>Source Th./Ex.</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{BR}_{B_s \rightarrow \mu^+ \mu^-}$</td>
<td>[41] / [42]</td>
<td>$1.117 ± 0.076_{\text{EX}} + 0.082_{\text{SM}} + 0.050_{\text{SU}}$</td>
</tr>
<tr>
<td>$\text{BR}(B_s \rightarrow \mu^+ \mu^-)$</td>
<td>[27] / [37]</td>
<td>$&lt; 1.8 ± 0.02_{\text{SU}}$</td>
</tr>
<tr>
<td>$\Delta M_{B_s}$</td>
<td>[45] / [47, 48]</td>
<td>$&lt; 0.97 ± 0.01_{\text{EX}} ± 0.27_{\text{SM}}$</td>
</tr>
<tr>
<td>$\Delta M_{B_d}$</td>
<td>[45] / [47, 48]</td>
<td>$&lt; 1.00 ± 0.01_{\text{EX}} ± 0.13_{\text{SM}}$</td>
</tr>
<tr>
<td>$\Delta a_\mu - a_\mu^{\text{SM}}$</td>
<td>[49] / [38, 50]</td>
<td>$(30.2 ± 8.8 ± 2.0_{SU}) × 10^{-10}$</td>
</tr>
<tr>
<td>$M_h$ [GeV]</td>
<td>[26] / [51, 52]</td>
<td>$&gt; 114.4 ± 1.5_{SU}$</td>
</tr>
<tr>
<td>$\Omega_{\text{CDM}} h^2$</td>
<td>[29] / [53]</td>
<td>$0.1169 ± 0.0056 ± 0.012_{SU}$</td>
</tr>
<tr>
<td>$\sigma_0^0$</td>
<td>[23]</td>
<td>$(m_{\chi_1^0}, \sigma_0^0)$ plane</td>
</tr>
<tr>
<td>jets + $E_T$</td>
<td>[16, 18]</td>
<td>$(m_0, m_{1/2})$ plane</td>
</tr>
<tr>
<td>$H / A, H^\pm$</td>
<td>[19]</td>
<td>$(M_A, \tan \beta)$ plane</td>
</tr>
</tbody>
</table>

**Flavour physics observables**
(largest impact $b \rightarrow s \gamma$, $B_s \rightarrow \mu \mu$)

**Higgs Mass**

**Cold Dark matter density**

**LHC direct searches**
Global Fits

Best fit contours in $\tan\beta$ vs $M_A$ plane in the NUHM1 model, [O. Buchmuller et al, arxiv:0907.5568] (pre-LHC results)

Low $\tan(\beta)$ and heavy Higgs mass $\sim$ 300 GeV
Global Fits: masterCode

F. Ronga at Workshop  LHC results for TeV scale physics, CERN, August 2011

\[ \tan \beta \text{ vs } M_A \text{ plane} \]

- CMSSM and NUHM1 still on the safe(ish) side
  - new 1/fb LHC data significantly pushes the allowed mass scale up
  - effect visible on \( M_A \) and \( \tan \beta \) as well
  - low \( \tan \beta \) no longer favoured!

.. Remember that \( B_s \to \mu \mu \) is proportional to \( \tan^6 \beta \).
Global Fits & $B_s \rightarrow \mu \mu$

- LHC 2011 MET searches only
Global Fits & $B_s \rightarrow \mu\mu$

- LHC 2011 MET searches and $B_s \rightarrow \mu\mu$

Bs$\rightarrow\mu\mu$ upper limit pushes down tan(β)
(opposite direction wrt direct searches)
No New Physics…
No New Physics...yet!
Projections for early 2012: LHCb

• Luminosity projections from present data-taking assume that LHCb will collect between $1 \text{ fb}^{-1}$ by the end of the year

For the winter conferences (assuming no changes in the analysis / data quality) $ightarrow$ LHCb might put a limit down to $(6-7) \times 10^{-9} @ 95\% \text{CL}$
Projections for early 2012: LHCb

• Luminosity projections from present data-taking assume that LHCb will collect between 1 fb$^{-1}$ by the end of the year.

… or could claim a 3 sigma evidence if the BR is $\sim 8 \times 10^{-9}$
Projections for CMS and LHCb

$3\sigma /5\sigma$ observations

Figure 18: Required luminosity in order to provide a $3\sigma$ evidence (orange) or a $5\sigma$ discovery (green) of a given $BR(B_s \rightarrow \mu^+\mu^-)$ on the left for LHCb and on the right for CMS.

a $3\sigma$ evidence for $BR = BR \sim 8 \times 10^{-9}$ will require:

1 $fb^{-1}$ for LHCb and 5 $fb^{-1}$ for CMS
Integrated Luminosity delivered to each LHC experiment (updated yesterday)

L(CMS)/L(LHCb) \sim 3.4
Projections for early 2012:
CMS+LHCb combination: \textbf{3 sigma evidence}

\textit{Standard model}

$L=3xL(EPS) \ [\sim 1 \text{ fb}^{-1} \text{ for LHCb, } \sim 3.3 \text{ fb}^{-1} \text{ for CMS}]$

Figure 19: Required luminosity in order to provide a 3\sigma evidence (orange) or a 5\sigma discovery (green) of a given BR($B_s \rightarrow \mu^+\mu^-$) for LHCb and CMS combined. The luminosity is expressed in terms of the luminosity used in [13], (0.34 fb$^{-1}$ for LHCb and 1.14 fb$^{-1}$ for CMS).

LHCb-CMS combined could claim a 3\sigma evidence if BR=(5-6)x10^{-9} by 2012 winter conferences.
B_{s} \rightarrow \mu \mu \text{ and } 4^\text{th} \text{ generation}

Preliminary projections for 2012 winter conferences for exclusion limits @ 95% CL:
Conclusions

Excess of $B_s \rightarrow \mu\mu$ events seen by CDF not confirmed. LHCb with 300 pb$^{-1}$ has put the best world upper limit:

$$\text{BR}(B_s \rightarrow \mu\mu) < 1.5 \times 10^{-8} \text{ @ 95\% CL}$$

LHCb combined with CMS brings the limit down to:

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

This limit has a direct impact on the global fits and on 4$^{\text{th}}$ generation models.

The best has to come… Wait for Winter Conferences..
STOP
Projections for early 2012: LHCb

- Luminosity projections from present data-taking assume that LHCb will collect between $1 \text{ fb}^{-1}$ by the end of the year

CAVEAT: Given the present accuracy on $fd/fs$ ($\sim 8\%$) and $\text{BR(SM)}$ predictions ($\sim 6\%$) only if $\text{BR (NP)}$ is larger than $1.3 \times \text{BR(SM)}$ ($\text{BR}>4.2 \times 10^{-9}$) we can exclude SM-like rate at 3 $\sigma$
LHCb trigger for $B_{s,d} \rightarrow \mu\mu$

Muon Lines

<table>
<thead>
<tr>
<th>Level</th>
<th>Muon Lines</th>
</tr>
</thead>
<tbody>
<tr>
<td>L0 e, $\gamma$</td>
<td>Single-$\mu$: $p_T &gt; 1.5$ GeV/c $\mu\mu$: $\sqrt{p_{T1} \times p_{T2}} &gt; 1.3$ GeV/c</td>
</tr>
<tr>
<td>L0 had</td>
<td></td>
</tr>
<tr>
<td>L0 $\mu$</td>
<td></td>
</tr>
</tbody>
</table>

HLT1

- single-$\mu$: $p_T > 1.8$ GeV/c
- IP > 0.01 mm

HLT2

- Several dimuon lines with $M_{\mu\mu}$ cuts and/or displaced vertex
- Global Event Cuts for events with high multiplicity

- 1/3 of the bandwidth (~0.8 kHz) given to the muon lines
- $p_T$ cuts on muon lines kept very low $\rightarrow \varepsilon$(trigger $B_{sd} \rightarrow \mu\mu$) ~ 90%
- Trigger rather stable during the whole period
The LHCb hunt for non-SM Higgs(es)

\[ B_{(d,s)} \rightarrow \mu\mu \] is the best way for LHCb to constrain the parameters of the extended Higgs sector in MSSM, fully complementary to direct searches.

\[
BR(B_q \rightarrow \ell^+\ell^-) \approx \frac{G_F^2 \alpha^2 M_{B_q}^3 f_{B_q}^2 |V_{tb}V_{tq}^*|^2}{64\pi^3 \sin^4 \theta_W} \sqrt{1 - \frac{4m_l^2}{M_{B_q}^2}} \left( \frac{2m_l}{M_{B_q}} \right) c_s^2 + \left( M_{B_q} c_P + \frac{2m_l}{M_{B_q}} (c_A - c'_A) \right)^2.
\]

Double suppressed decay: **FCNC process** and **helicity suppressed**:  
→ very small in the Standard Model but very well predicted:

\[ B_s \rightarrow \mu^+\mu^- = (3.2\pm0.2) \times 10^{-9} \]
\[ B_d \rightarrow \mu^+\mu^- = (1.0\pm0.1) \times 10^{-10} \]

Parameterization of the BR\((B_s \rightarrow \mu\mu)\) in terms of SM quantities:

\[
BR(B_s \rightarrow \mu^+\mu^-)_{SM} = 3.5 \times 10^{-9} \times \frac{\tau_s}{1.6 \text{ ps}} \times \left( \frac{f(B_s)}{210 \text{ MeV}} \right)^2 \times \left( \frac{|V_{ts}|}{0.04} \right)^2 \times \left( \frac{m_{top}}{170 \text{ GeV/c}^2} \right)^{3.12}
\]

The (dominant) error on \( f(B_s) \) has been replaced by the error on \( \Delta M \).
Normalization

- The signal PDFs can be translated into a number of expected signal events by normalizing to a channel with known BR

\[
\text{BR} = \text{BR}_{\text{cal}} \times \frac{\epsilon_{\text{cal}}^{\text{REC}} \epsilon_{\text{cal}}^{\text{SEL}|\text{REC}} \epsilon_{\text{cal}}^{\text{TRIG}|\text{SEL}}}{\epsilon_{\text{sig}}^{\text{REC}} \epsilon_{\text{sig}}^{\text{SEL}|\text{REC}} \epsilon_{\text{sig}}^{\text{TRIG}|\text{SEL}}} \times \frac{f_{\text{cal}}}{f_{B_s^0}} \times \frac{N_{B_s^0 \rightarrow \mu^+ \mu^-}}{N_{\text{cal}}} = \alpha \times N_{B_s^0 \rightarrow \mu^+ \mu^-}
\]

Three different channels used:

1) \( \text{BR}(B^+ \rightarrow J/\psi(\mu^+ \mu^-) K^+) = (5.98 \pm 0.22) \times 10^{-5} \quad \text{3.7\% uncertainty} \)  
   - Similar trigger and PID. Tracking efficiency (+1 track) dominates the systematic in the ratio of efficiencies. Needs \( f_d/f_s \) as input: 13\% uncertainty

2) \( \text{BR}(B_s \rightarrow J/\psi(\mu^+ \mu^-) \phi(K^+K^-)) = (3.35 \pm 0.9) \times 10^{-5} \quad \text{26\% uncertainty} \)  
   - Similar trigger and PID. Tracking efficiency (+2 tracks) dominates the systematic

3) \( \text{BR}(B^0 \rightarrow K^+\pi^-) = (1.94 \pm 0.06) \times 10^{-5} \quad \text{3.1\% uncertainty} \)  
   - Same topology in the final state. Different trigger dominate the syst. Needs \( f_d/f_s \)
<table>
<thead>
<tr>
<th>Invariant Mass bins (MeV/c²)</th>
<th>Geometrical Likelihood Bins</th>
<th>([0, 0.25])</th>
<th>([0.25, 0.5])</th>
<th>([0.5, 0.75])</th>
<th>([0.75, 1])</th>
</tr>
</thead>
<tbody>
<tr>
<td>([-60, -40])</td>
<td>Exp. bkg.</td>
<td>56.9^{+1.1}_{-1.1}</td>
<td>1.31^{+0.19}_{-0.17}</td>
<td>0.282^{+0.076}_{-0.065}</td>
<td>0.016^{+0.021}_{-0.010}</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>0.0076^{+0.0034}_{-0.0030}</td>
<td>0.0050^{+0.0027}_{-0.0020}</td>
<td>0.0037^{+0.0015}_{-0.0011}</td>
<td>0.0047^{+0.0015}_{-0.0010}</td>
</tr>
<tr>
<td>([-40, -20])</td>
<td>Exp. bkg.</td>
<td>56.1^{+1.1}_{-1.1}</td>
<td>1.28^{+0.18}_{-0.17}</td>
<td>0.269^{+0.072}_{-0.062}</td>
<td>0.015^{+0.020}_{-0.009}</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>0.0220^{+0.0084}_{-0.0079}</td>
<td>0.0146^{+0.0066}_{-0.0053}</td>
<td>0.0107^{+0.0036}_{-0.0026}</td>
<td>0.0135^{+0.0034}_{-0.0024}</td>
</tr>
<tr>
<td>([-20, 0])</td>
<td>Exp. bkg.</td>
<td>55.3^{+1.1}_{-1.1}</td>
<td>1.24^{+0.17}_{-0.16}</td>
<td>0.257^{+0.069}_{-0.059}</td>
<td>0.014^{+0.018}_{-0.009}</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>0.038^{+0.015}_{-0.014}</td>
<td>0.025^{+0.012}_{-0.010}</td>
<td>0.0183^{+0.0063}_{-0.0047}</td>
<td>0.0235^{+0.0059}_{-0.0042}</td>
</tr>
<tr>
<td>([0, 20])</td>
<td>Exp. bkg.</td>
<td>54.4^{+1.1}_{-1.1}</td>
<td>1.21^{+0.17}_{-0.16}</td>
<td>0.246^{+0.066}_{-0.057}</td>
<td>0.013^{+0.017}_{-0.008}</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>0.0376^{+0.015}_{-0.015}</td>
<td>0.025^{+0.012}_{-0.010}</td>
<td>0.0183^{+0.0063}_{-0.0047}</td>
<td>0.0235^{+0.0060}_{-0.0044}</td>
</tr>
<tr>
<td>([20, 40])</td>
<td>Exp. bkg.</td>
<td>53.6^{+1.1}_{-1.0}</td>
<td>1.18^{+0.17}_{-0.15}</td>
<td>0.235^{+0.063}_{-0.054}</td>
<td>0.012^{+0.015}_{-0.007}</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>0.0220^{+0.0084}_{-0.0081}</td>
<td>0.0146^{+0.0067}_{-0.0054}</td>
<td>0.0107^{+0.0036}_{-0.0027}</td>
<td>0.0135^{+0.0035}_{-0.0025}</td>
</tr>
<tr>
<td>([40, 60])</td>
<td>Exp. bkg.</td>
<td>52.8^{+1.0}_{-1.0}</td>
<td>1.15^{+0.16}_{-0.15}</td>
<td>0.224^{+0.060}_{-0.052}</td>
<td>0.011^{+0.014}_{-0.007}</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>0.0076^{+0.0031}_{-0.0027}</td>
<td>0.0050^{+0.0025}_{-0.0019}</td>
<td>0.0037^{+0.0013}_{-0.0010}</td>
<td>0.0047^{+0.0013}_{-0.0010}</td>
</tr>
</tbody>
</table>
The models: 1.) CMSSM (or mSUGRA):

⇒ Scenario characterized by

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

\[ m_0 : \text{universal scalar mass parameter} \]
\[ m_{1/2} : \text{universal gaugino mass parameter at the GUT scale} \]
\[ A_0 : \text{universal trilinear coupling} \]
\[ \tan \beta : \text{ratio of Higgs vacuum expectation values} \]
\[ \text{sign}(\mu) : \text{sign of supersymmetric Higgs parameter} \]

⇒ particle spectra from renormalization group running to weak scale
The models: 2.) **NUHM1:** (Non-universal Higgs mass model)

**Assumption:** no unification of *scalar fermion* and *scalar Higgs* parameter at the GUT scale

⇒ effectively $M_A$ or $\mu$ as free parameters at the EW scale

⇒ besides the CMSSM parameters

$M_A$ or $\mu$

Further extension: **NUHM2:**

**Assumption:** no unification of the Higgs parameters at the GUT scale

⇒ effectively $M_A$ and $\mu$ as free parameters at the EW scale

⇒ besides the CMSSM parameters

$M_A$ and $\mu$
The models: 3.) **VCMSSM**: (Very Constrained MSSM)

⇒ In addition to CMSSM: assume relation between $A_0$ and $m_0$:

$$A_0 = m_0 + B_0$$

tan $\beta$ fixed (e.g. via CDM constraint)

Free parameters: $m_{1/2}$, $A_0$, $m_0$

Lightest SUSY particle (LSP) is the lightest neutralino

The models: 4.) **mSUGRA**: (Gravitino DM in mSUGRA)

⇒ In addition to CMSSM: assume relation between $A_0$ and $m_0$:

$$A_0 = m_0 + B_0$$

**mSUGRA**: $m_{\text{gravitino}} = m_0$ ⇒ gravitino can be the LSP

Free parameters: $m_{1/2}$, $A_0$, $m_0$

Lightest SUSY particle (LSP) is the gravitino