New results on the search for $B_s \rightarrow \mu^+\mu^-$ from LHCb

Johannes Albrecht (CERN & TU Dortmund)
on behalf of the LHCb Collaboration

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Kyoto, Japan
Double suppressed decay: **FCNC process** and **helicity suppressed**:  

→ **BR very small in the Standard Model but well predicted:**

<table>
<thead>
<tr>
<th>Mode</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_s \to \mu^+\mu^-, \text{ time averaged})</td>
<td>((3.54 \pm 0.30) \times 10^{-9})</td>
</tr>
<tr>
<td>(B^0 \to \mu^+\mu^-)</td>
<td>((0.107 \pm 0.01) \times 10^{-9})</td>
</tr>
</tbody>
</table>


**BR expressed in Wilson coefficients:**

\[
BR(B_s \to \mu^+\mu^-) \propto |C_S - C'_S|^2 \left(1 - \frac{4m_{\mu}^2}{m_{B_s}^2}\right) + \left|(C_P - C'_P) + \frac{2m_{\mu}}{m_{B_s}}(C_{10} - C'_{10})\right|^2
\]

→ sensitive to contributions in the **scalar/pseudo-scalar sector**

→ highly interesting to probe **extended Higgs** models

→ **Constrained SUSY models at high tan\(\beta\):**  
\(B_{s,d} \to \mu^+\mu^-\) more sensitive than direct searches
ABSTRACT. Using the ARGUS detector at the $e^+e^-$ storage ring DORIS II, we have studied the colour-suppressed decays $B \rightarrow J/\psi X$ and $B \rightarrow \psi' X$. We find the inclusive branching ratios for these two channels to be $(1.07 \pm 0.16 \pm 0.19)\%$ and $(0.46 \pm 0.17 \pm 0.11)\%$ respectively. From a sample of reconstructed exclusive events the masses of the $B^0$ and $B^+$ mesons are determined to be $(5279.5 \pm 1.6 \pm 3.0)\ MeV/c^2$ and $(5278.5 \pm 1.8 \pm 3.0)\ MeV/c^2$ respectively. Branching ratios are determined from five events of the type $B^0 \rightarrow J/\psi K^*$ and three of $B^+ \rightarrow J/\psi K^+$. In the same data sample a search for $B^0 \rightarrow e^+e^-, \mu^+\mu^-, \text{and} \ \mu^\pm e^\mp$ leads to upper limits for such decays.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Upper limits for exclusive dilepton decays.</th>
</tr>
</thead>
<tbody>
<tr>
<td>decay channel</td>
<td>upper limit with 90% CL</td>
</tr>
<tr>
<td>$B^0 \rightarrow e^+e^-$</td>
<td>$8.5 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \mu^+\mu^-$</td>
<td>$5.0 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow e^\pm \mu^\mp$</td>
<td>$5.0 \cdot 10^{-5}$</td>
</tr>
</tbody>
</table>
Experimental status: recent

- Search for $B_s \rightarrow \mu^+\mu^-$ decays ongoing since 25 years

- Sensitivity of CMS & LHCb very close to SM prediction

Best limit $\sim 1.2 \times$ SM prediction $\rightarrow$ large enhancements excluded
LHCb analysis
1.0 fb$^{-1}$ (2011) + 1.1 fb$^{-1}$ (2012)

One of the best signal candidates in the 2012 dataset

BDT=0.826 and $m_{\mu\mu} = 5353$ MeV/c$^2$
Datasets

- Combined analysis of the following datasets:
  - 1.1 fb\(^{-1}\) of data at \(\sqrt{s}=8\text{TeV}\) (2012) increased b\(\bar{b}\)-production cross section
  - 1.0 fb\(^{-1}\) of data at \(\sqrt{s}=7\text{TeV}\) (2011)

- First analysis of the data recorded in 2011 published \textit{PRL108}(2012)231801
  - Measurement presented here is similar to this previous analysis
  - improvements over the previous publication are implemented

- Full 2011 data set reanalysed
  \(\Rightarrow\) It supersedes the previous publication
LHCb analysis I

• **Selection**
  
  – Soft selection to reduce size of dataset, similar to control channels unchanged to previous analyses

• **Normalization**

  – Convert number of observed events in branching fraction by normalizing to \( B^{\pm} \to J/\psi K^{\pm} \) and \( B \to K^{+}\pi' \)

\[
BR = BR_{\text{cal}} \cdot \frac{\varepsilon_{\text{cal}}^{\text{Rec}} \cdot \varepsilon_{\text{cal}}^{\text{Sel}}}{\varepsilon_{\text{Bs}}^{\text{Rec}} \cdot \varepsilon_{\text{Bs}}^{\text{Sel}}} \cdot \frac{f_{\text{cal}}}{f_{B_{s}}} \cdot \frac{N_{B^{\pm} \to \mu\mu}}{N_{\text{cal}}} = \alpha \cdot N_{B^{\pm} \to \mu\mu}
\]

- from MC
- from data checked
- from data
- fraction \( b \to B_{s} \)
- (updated, next slide)

Slightly lower than in 2011 measurement due to higher \( \mathcal{L} \) and x-section

**Normalization factors**

\[
\alpha(B_{s}^{0} \to \mu^{+}\mu^{-}) = (2.52 \pm 0.23) \times 10^{-10}
\]

\[
\alpha(B^{0} \to \mu^{+}\mu^{-}) = (6.45 \pm 0.30) \times 10^{-11}
\]
b fragmentation $f_d/f_s$ (updated)

- LHCb has measured the fraction of $b \rightarrow B_s$ in two ways:
  - Ratio of $B_s \rightarrow D_s \mu X$ to $B \rightarrow D^+ \mu X$
  - Ratio of $B_s \rightarrow D_s \pi^+$ to $B \rightarrow D^+ K$ and $B^0 \rightarrow D^+ \pi^+$

- Combined result

\[
\frac{f_s}{f_d} = 0.256 \pm 0.020
\]

- Found to be dependent of $p_T$
  - For the $p_T$ values involved: effect smaller than 0.02 $\rightarrow$ negligible

- Stability 7 vs 8 TeV checked
  - $B^+ \rightarrow J/\psi K^+ / B_s \rightarrow J/\psi \phi$ ratio stable

[PRD85 (2012) 032008]
(newly updated: $1fb^{-1} @ 7$ TeV)

[LHCb-PAPER-2012-037] in preparation
LHCb analysis II

- **Signal likelihood**
  - BDT for signal classification (unchanged to previous analysis)
    - Signal PDF calibrated with $B_{(s)} \rightarrow h^+h^-$
    - Compared to 2011 analysis, BDT shape moved to slightly lower values
  - Invariant mass, resolution:
    - $\sigma(B^0 \rightarrow \mu\mu) = 24.63 \pm 0.38^{\text{stat+syst}} \text{ MeV}/c^2$
    - $\sigma(B_s \rightarrow \mu\mu) = 25.04 \pm 0.40^{\text{stat+syst}} \text{ MeV}/c^2$
    - Well comparable to 2011 analysis

- **Background likelihood**:
  - Main background: combinatorial from $bb \rightarrow \mu^+\mu^-X$
    - background extrapolated from sideband
  - Improved description of peaking background below signal window (see next slide)

- Extraction of the result
  - Extract observation / exclusion measurement using the CLs method
  - Determine branching fraction with unbinned ML fit
Improvement of combinatorial background interpolation by inclusion of backgrounds from exclusive decays in the fit

- Contribution in signal window: only $B_{(s)} \rightarrow h^+h^-$ (identical treatment as 2011)
- Mass shape different from exponential → bias the background interpolation (new):
  - $B^0 \rightarrow \pi^+\mu^-\nu$
  - $B^+ \rightarrow \pi^+\mu^+\mu^-$, $B^0 \rightarrow \pi^0\mu^+\mu^-$ (considered together)

Both have a negligible contribution in the $B^0$ and $B_s$ mass windows

Exclusive background parameters used as priors in the fit (allowed to vary within $1\sigma$)

- Yield from relative normalization to $B^+ \rightarrow J/\psi K^+$
- Mass and BDT shape from full MC

Background systematic reduced (2011 was comparison exp-double exp)
Observed pattern of events

- Mass sideband fit to extrapolate background
  - Combinatorial background and
    \( B^0 \rightarrow \pi^+\mu^+\nu \)
    \( B \rightarrow \pi\mu^+\mu^- \)
    \( B_{(s)} \rightarrow h^0h^0 (\text{misID}) \)

- Same fit has been repeated on 2011
  - Combinatorial component reduced in high BDT bins
  - Impact on published results evaluated

2012, 1.1 fb^{-1} @ \sqrt{s}=8\text{TeV}

Highest BDT bin: no events in sidebands \( \rightarrow \) merge two highest bins

2011, 1.0 fb^{-1} @ \sqrt{s}=7\text{TeV}
Results for $B^0 \to \mu^+\mu^-$

- Evaluate compatibility with background only and signal+background hypotheses (CLs method)
  - Combined 2011+2012 dataset used
  - bkg only p-value: 11%
  - Upper exclusion limit
    $BR(B^0 \to \mu^+\mu^-) < 9.4 \times 10^{-10}$
    @95% CL
    world best single experiment

<table>
<thead>
<tr>
<th>$B^0 \to \mu^+\mu^-$</th>
<th>expected (bkg)</th>
<th>expected (SM+bkg)</th>
<th>observed</th>
<th>1-CLb</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>$9.6 \times 10^{-10}$</td>
<td>$10.5 \times 10^{-10}$</td>
<td>$12.5 \times 10^{-10}$</td>
<td>0.16</td>
</tr>
<tr>
<td>2011+2012</td>
<td>$6.0 \times 10^{-10}$</td>
<td>$7.1 \times 10^{-10}$</td>
<td>$9.4 \times 10^{-10}$</td>
<td>0.11</td>
</tr>
</tbody>
</table>
Results for $B_s \rightarrow \mu^+\mu^-$: Limits and significance

- Evaluate compatibility with background only and background+signal hypotheses (CLs method)
  - 2011+2012:
    - bkg only p-value: $5 \times 10^{-4}$
      (corresponds to 3.5$\sigma$)
    - 2012 alone
      - bkg only p-value: $9 \times 10^{-4}$
        (corresponds to 3.3 $\sigma$)
  - Double sided limit (@95% CL)
    $$1.1 \times 10^{-9} < BR(B_s \rightarrow \mu^+\mu^-) < 6.4 \times 10^{-9}$$

- This is the first evidence of the decay $B_s \rightarrow \mu^+\mu^-$!
Results for $B_s \rightarrow \mu^+ \mu^-$: BR fit

- Simultaneous unbinned likelihood fit to 15 BDT bins of 2011 + 2012
  - Combinatorial bkg, $B_s$ and $B^0$ yield fully free
  - Exclusive backgrounds inserted as Gaussian constraints

- Fit result:

$$BR(B_s \rightarrow \mu^+ \mu^-) = 3.2^{+1.4}_{-1.2} (\text{stat}) ^{+0.5}_{-0.3} (\text{syst}) \times 10^{-9}$$

- Systematic Uncertainties
  - Change bkg model
  - Fix all Gaussian constraints

2011, 1.1fb$^{-1}$ @ $\sqrt{s}=7$TeV

2012, 1.1fb$^{-1}$ @ $\sqrt{s}=8$TeV
Conclusions

- Combined analysis on $1.0 \text{fb}^{-1} @ \sqrt{s}=7 \text{TeV}$ and $1.1 \text{fb}^{-1} @ \sqrt{s}=8 \text{TeV}$
- Upper exclusion limit @ 95% CL
  $\text{BR}(B^0 \rightarrow \mu^+ \mu^-) < 9.4 \times 10^{-10}$
  worlds best single experiment limit
- Excess of $B_s \rightarrow \mu^+ \mu^-$ candidates with a signal significance of to 3.5 standard deviations
  (bkg only p-value: $5 \times 10^{-4}$)
- The branching fraction is measured as

  $BR(B_s \rightarrow \mu^+ \mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$
First evidence for the decay $B_s^0 \rightarrow \mu^+\mu^-$

The LHCb collaboration

A search for the rare decays $B_s^0 \rightarrow \mu^+\mu^-$ and $B^0 \rightarrow \mu^+\mu^-$ is performed using data collected in 2011 and 2012 with the LHCb experiment at the Large Hadron Collider. The data samples comprise 1.1 fb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 8$ TeV and 1.0 fb$^{-1}$ at $\sqrt{s} = 7$ TeV. We observe an excess of $B_s^0 \rightarrow \mu^+\mu^-$ candidates with respect to the background expectation. The probability that the background could produce such an excess or larger is $5.3 \times 10^{-4}$ corresponding to a signal significance of 3.5 standard deviations. A maximum-likelihood fit gives a branching fraction of $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$, where the statistical uncertainty is 95% of the total uncertainty. This result is in agreement with the Standard Model expectation. The observed number of $B^0 \rightarrow \mu^+\mu^-$ candidates is consistent with the background expectation, giving an upper limit of $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 9.4 \times 10^{-10}$ at 95% confidence level.

Will be submitted to arXiv & PRL today.
Precise predictions

\[ B_s \rightarrow \mu^+\mu^- \]

Slide shown to the CERN Scientific Policy Committee in December 2007

- \( B \rightarrow \mu \) and \( B \rightarrow \mu \) select
  - specific background dominated by \( B_c \rightarrow J/\psi(\mu\mu)\mu\nu \)
  - Exploit good detector performance:
    - muon ID
    - vertexing (topology)
    - mass resolution (18 MeV/c^2)

- 0.05 fb\(^{-1} \) ⇒ overtake CDF+D0
- 0.5 fb\(^{-1} \) ⇒ exclude BR values down to SM
- 2 fb\(^{-1} \) ⇒ 3\( \sigma \) evidence of SM signal
- 6 fb\(^{-1} \) ⇒ 5\( \sigma \) observation of SM signal

90% CL limit on BR
(only bkg is observed)

Expected final CDF+D0 limit
Uncertainty in background prediction

SM prediction

Integrated luminosity (fb\(^{-1} \))

LHCb’s best NP discovery potential
with the very early data!

O. Schneider, Dec 10, 2007
Results for $B_s \rightarrow \mu^+\mu^-$: BR fit

- Perform simultaneous unbinned likelihood fit to 15 BDT bins of 2011 + 2012
  - Exponential slope+normalization, $B_s$ and $B^0$ yield fully free
  - Signal fractions in BDT from $B \rightarrow h^+h^-$
  - Gaussian constraint to
    - Exclusive background parameters
    - $B \rightarrow h^+h^-$ misID
  - Fit result:

  $BR(B_s \rightarrow \mu^+\mu^-) = 3.2^{+1.4}_{-1.2} \text{(stat)}^{+0.5}_{-0.3} \text{(syst)} \times 10^{-9}$

- Evaluate systematics with
  - Change bkg model
  - Fix all Gaussian constraints

  $\rightarrow$ BR fully dominated by stat
Cross check 2011 only

- Check the effect of refined background analysis on 2011
  - Analysis identical to published one PRL PRL108(2012)231801
  - Update fits for combinatorial background and BR
    \[ \text{UL} \ 4.5 \rightarrow 5.1 \times 10^{-9} \]
    \[ \text{BR} \ 0.8 \rightarrow 1.3 \times 10^{-9} \ (\sim 0.3\sigma_{\text{stat}} \text{ or } \sim 1\sigma_{\text{syst}}) \]

- Effect of newly considered exclusive background components consistent with the systematic uncertainty assigned due to lack of knowledge of the background in previous analysis.
Signal likelihood definition

- Construct BDT of 9 input variables:
  - B impact parameter, lifetime, PT, isolation
  - Muon min PT, polarization, IP, DOCA, isolation
- Choice of variables to avoid correlation with invariant mass
- Optimization and training on MC ($B_{s,d} \rightarrow \mu^+\mu^-$ and $bb \rightarrow \mu^+\mu^- X$ background)
- Calibrate PDF shape using $B_{(s)} \rightarrow h^+h^\prime$
Signal likelihood calibration

- BDT calibration with \( B_{(s)} \rightarrow h^+h^- \):
  - identical decay topology to signal
  - Use events triggered independent of signal to avoid trigger bias

- **Signal distribution in BDT flat as expected from simulation**

- Signal invariant mass modelled with a crystal ball
  - Resolution obtained from data:
    - Interpolation between dilepton resonances (\( J/\psi, \psi(2S) \) and \( \Upsilon \))
    - Inclusive \( B \rightarrow h^+h^- \)
  - \( \rightarrow \) weighted average:
    \[
    \sigma(B^0 \rightarrow \mu\mu) = 24.63 \pm 0.38^{\text{stat+syst}} \text{ MeV/c}^2
    \]
    \[
    \sigma(B_s \rightarrow \mu\mu) = 25.04 \pm 0.40^{\text{stat+syst}} \text{ MeV/c}^2
    \]
Impact of $B_s \rightarrow \mu^+\mu^-$ on SUSY

- Global fit to flavour and high PT observables
  - Includes Higgs and SUSY direct searches, XENON100, EW and flavour measurements
- Done for constrained SUSY models, here CMSSM (NUHM1 similar)

$$m_0 [\text{GeV}]$$

$$m_{1/2} [\text{GeV}]$$

CMS with 4.4 fb$^{-1}$ (1.1 fb$^{-1}$)

LHCb+CMS (0.3+1.1) fb$^{-1}$

F. Mahmoudi, [1205.3099]
Impact of $B_s \rightarrow \mu^+ \mu^-$ on SUSY

- Global fit to flavour and high PT observables
  - Includes Higgs and SUSY direct searches, XENON100, EW and flavour measurements
- Done for constrained SUSY models, here CMSSM (NUHM1 similar)

CMS with 4.4$fb^{-1}$ (1.1$fb^{-1}$)  
LHCb 1$fb^{-1}$

Limits on $B_s \rightarrow \mu^+ \mu^-$ disfavour constrained SUSY at high $\tan \beta$

12. November 2012

Johannes Albrecht