Probing new physics in $B_s \rightarrow \mu^+ \mu^-$ at LHCb

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Outline

- Motivation of $B_s \rightarrow \mu \mu$ as a probe of NP
- Analysis in LHCb
  - Overview
  - Calibration and normalization
- First results
- Conclusions
Motivation of $B_s \to \mu\mu$ as a probe of NP
Indirect approach

- $B_s \rightarrow \mu\mu$ can access NP through new virtual particles entering in the loop → indirect search of NP

- Indirect approach can access higher energy scales and see NP effects earlier:
  - Done before in the history of physics...
    - 3rd quark family inferred by Kobayashi and Maskawa (1973) to explain CPV in K mixing (1964). Directly observed in 1977 (b) and 1995 (t)
    - Neutral Currents discovered in 1973, $Z^0$ directly observed in 1983

\[ \text{~30 years till the direct observation...} \]
Decay Physics (SM)

- Hadronic weak decays are often studied in terms of effective hamiltonians of local operators. Degrees of freedom of exchanged particles are integrated out giving rise to the **Wilson coefficients** $C_i$.

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

$$\times \left\{ M_{B_q}^2 \left( 1 - \frac{4m_{\mu}^2}{M_{B_q}^2} \right) C_s^2 + \left[ M_{B_q}^2 C_p^2 + \frac{2m_{\mu}}{M_{B_q}} C_{10} \right]^2 \right\}$$

- $C_{s,p}$ are negligible in **SM**, $C_{10}$ gives the **only relevant contribution**.

This decay is very suppressed in SM:

$$BR(B_s \rightarrow \mu\mu) = (3.35 \pm 0.32) \cdot 10^{-9}$$  
M. Blanke et al., JHEP 10 003, 2006

- Current experimental upper limit (CDF, 2fb$^{-1}$) still one order of magnitude above these values. @ 90% CL:

$$BR(B_s \rightarrow \mu\mu) < 3.6 \cdot 10^{-8}$$  
CDF collab., CDF Public Note 9892

* $BR(B_d \rightarrow \mu\mu) = (1.03 \pm 0.09) \cdot 10^{-10}$
New Physics effects

- NP can contribute to this decay rate (specially SUSY at high $\tan\beta$ ($\tan\beta = v_u/v_d$)):
  - More than one Higgs → contributions to $C_{S,P}$
    - 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 $C_{10}$.

NP can modify the BR from smaller SM up to current experimental upper limit → **Any measured value will affect NP searches!**
Analysis in LHCb

Overview
LHCb overview

LHCb overview

Magnet

RICH-1

VELO

TT

Tracker

OT

IT

RICH-2

Calorimeters

ECal

HCal

Muon System

SPD

PS
LHCb overview

**Physics**: Examples of key channels
- Rare decays: $B_s \rightarrow \mu \mu$, $B_d \rightarrow K^* \mu \mu$
- CP Violation: $B_s \rightarrow J/\Psi \Phi$, $B_{s/d} \rightarrow hh$

**LHCb strong points**:
- PID
- Vertexing and IP
- Momentum and mass resolution
- Flexible trigger
LHCb overview

More on LHCb, see:
- **LHCb status and physics plans for 1fb⁻¹ run**
  by Eugeni Grauges
- **Flavor tagging at LHCb**
  by Marc Grabalosa

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**Physics:** Examples of key channels
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Analysis overview

- Selection: apply some cuts on all $\mu\mu$ candidates to remove most of the background.
- Classify each event using three properties (bins in a 3D parameter space):
  - **Particle Identification (PID):** Probability to be muons
  - **Geometrical properties** (Geometrical likelihood)
  - **Invariant Mass**
- 3D space is binned, so that each bin is treated as an independent experiment. Results combined using **Modified Frequentist Approach**

  see T. Junk NIM A434, 435, 1999

- Use of **control channels** to avoid dependence on simulation:
  - **Calibration of relevant variables**
  - **Normalization**
How is the Geometrical Likelihood built?

1. Input variables: min Impact Parameter Significance \((\mu^+,\mu^-)\), DOCA, Impact Parameter of B, lifetime, iso - \(\mu^+\), iso- \(\mu^-\)

- What is isolation? Fake \(B_s \rightarrow \mu\mu\) might originate in muons from another SV. For each muon, remove the other \(\mu\) and look at the rest of the event: How many good - SVs (forward, DOCA, pointing) can it make?

Distributions of some relevant variables from MC signal and background
How is the Geometrical Likelihood built?

1. Input variables: min Impact Parameter Significance \((\mu^+, \mu^-)\), DOCA, Impact Parameter of B, lifetime, iso - \(\mu^+\), iso- \(\mu^-\)
2. Transformed to Gaussian through cumulative and inverse error function
3. In such space correlations are more linear-like \(\rightarrow\) rotation matrix, and repeat 2
How is the Geometrical Likelihood built?

1. Input variables: min Impact Parameter Significance ($\mu^+, \mu^-$), DOCA, Impact Parameter of B, lifetime, iso - $\mu^+$, iso- $\mu^-$
2. Transformed to Gaussian through cumulative and inverse error function
3. In such space correlations are more linear-like $\rightarrow$ rotation matrix, and repeat 2
4. Transformations under signal hyp. $\rightarrow \chi^2_S$, under bkg. $\rightarrow \chi^2_B$.
5. Discriminating variable is $\chi^2_S - \chi^2_B$, flat again
Particles with associated hits after extrapolation to the muon chambers are flagged as muons

Some of them might not be actual muons (misidentification). Different subdetectors return probabilities for different kinds of particles, as seen before:
- Muon chambers: distances of hits to track extrapolation, or fit of the track to hits
- RICH: uses masses of the particles
- CALOs: energy deposition

Probabilities can be combined in a likelihood to fight against remaining misid
Signal 90% CL **exclusion sensitivity** as a function of Luminosity and time

- **Atlas**
- **CMS**
- **LHCb**

Assuming nominal luminosities since the beginning

- ATLAS/CMS $\rightarrow L = 10^{33} \, \text{cm}^{-2}\text{s}^{-1}$
- LHCb $\rightarrow L = 2 \times 10^{32} \, \text{cm}^{-2}\text{s}^{-1}$

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**CDF** (3.7fb$^{-1}$)  
90% CL exclusion

$BR(B_s^0 \rightarrow \mu^+ \mu^-) \times 10^{-9}$

**SM prediction**

**CDF + D0** (8fb$^{-1}$)

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**Atlas**

**CMS**

**LHCb**

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**MC sim.**

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**MC sim.**
Signal **evidence sensitivity** as a function of Luminosity and time

- Atlas
- CMS
- LHCb

Assuming nominal luminosities since the beginning

ATLAS/CMS $\rightarrow$ $L = 10^{33}$ cm$^{-2}$s$^{-1}$
LHCb $\rightarrow$ $L = 2 \times 10^{32}$ cm$^{-2}$s$^{-1}$

from MC sim.
Analysis in LHCb

→ Calibration and normalization
Calibration

- Signal is distributed in several bins of a 3D space
- We need to know both the overall normalization and the fraction of signal in each bin
  - **Invariant mass**: Can be calibrated, e.g., with fit of $B \rightarrow hh$ line shape or from charmonium and bottomonium resonances
  - **Geometrical Likelihood**: $B \rightarrow hh$ triggered independently of signal (event triggered by the other $B$)
  - **PID likelihood**: $J/\Psi$ taking $p$, $p_t$ distributions from $B \rightarrow hh$

- Will have a quick look at **invariant mass** and **geometrical likelihood**
Method 1: **Full fit of the $B \rightarrow hh$ line shape**
- Use the Geometrical Likelihood to clean the sample!

$$\text{GL} = [0.25-0.5] \quad \text{GL} = [0.5-0.75] \quad \text{GL} = [0.75-1.0]$$

<table>
<thead>
<tr>
<th></th>
<th>GL:[0.25-0.5]</th>
<th>GL:[0.5-0.75]</th>
<th>GL:[0.75-1.0]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{N}_{\text{tot}}$</td>
<td>703</td>
<td>661</td>
<td>695</td>
</tr>
<tr>
<td>$\sigma$ (MeV/c²)</td>
<td>$24.4 \pm 2.6$</td>
<td>$27.5 \pm 0.82$</td>
<td>$26.9 \pm 0.2$</td>
</tr>
<tr>
<td>$M(B_d)$ (MeV/c²)</td>
<td>$5276.6 \pm 4.3$</td>
<td>$5273 \pm 4.0$</td>
<td>$5273 \pm 0.71$</td>
</tr>
<tr>
<td>$M(B_s)$ (MeV/c²)</td>
<td>$5352.8 \pm 3.8$</td>
<td>$5359 \pm 3.2$</td>
<td>$5356 \pm 0.77$</td>
</tr>
</tbody>
</table>
Method 2: **Interpolation of $\sigma$ between charmoniums and bottomiums.**
- Correction for $B_s$ momentum spectrum.

\[
\sigma_{m_{B_s}} = (26.7 \pm 0.3) \text{ MeV/c}^2
\]
Fit the distribution in GL bins to extract the **number of B → hh signal events**.

- First bin difficult to fit. Get the number in this bin by:
  - Fitting all $B \rightarrow hh$ and subtracting events from other GL bins,
  - Cleaning with topological cuts before the fit and assessing signal loss via control channel.
Geometrical Likelihood calibration (II)

- GL distribution from $B \rightarrow hh$:

Normalised into a pdf, used in the computation of the limit.

Not as flat as expected. **Work ongoing to understand why!**
Normalization

- Normalization needed to convert # events into a BR without relying on knowledge of $\sigma_{bb}$, integrated luminosity or absolute efficiencies

\[
BR = \frac{BR_{cal} \cdot \varepsilon_{cal}^{Rec} \cdot \varepsilon_{cal}^{Sel} \cdot \varepsilon_{cal}^{GEC} \cdot \varepsilon_{cal}^{Trig} \cdot f_{cal} \cdot \frac{N_{B\rightarrow\mu\mu}}{N_{cal}}}{\varepsilon_{Bs}^{Rec} \cdot \varepsilon_{Bs}^{Sel} \cdot \varepsilon_{Bs}^{GEC} \cdot \varepsilon_{Bs}^{Trig} \cdot f_{Bs} \cdot N_{Bs\rightarrow\mu\mu}} = \text{norm} \cdot \frac{N_{B\rightarrow\mu\mu}}{N_{cal}}
\]

- $cal$: control channel
- $B_s$: $B_s \rightarrow \mu\mu$

- Using any, $B^+$, $B^d$ as a control channel implies a $\sim 13\%$ systematic from the knowledge of $f_d/f_s$ ($=f_+/f_s$). Normalization to a $B_s$ mode would introduce in principle larger errors because of worse known of branching ratios.

- Some control channel candidates:
  - $B^+ \rightarrow J/\Psi(\mu\mu)K^+$, $B_s \rightarrow J/\Psi(\mu\mu)\Phi(KK)$
    - similar trigger and PID,
    - different reconstruction because of the extra track/tracks
    - $B_s$: worse BR precision, but not $f_+/f_s$
  - $B \rightarrow hh$:
    - Same kinematics
    - different trigger & PID

Several groups in LHCb are measuring $f_d/f_s$. Hope to reduce the error soon to $\sim 7\%$
The fraction of efficiencies (trigger, reconstruction, selection, PID...) needs to be computed/cancelled.

Trigger on data:
- $J/\Psi$ trigger efficiency L0, HLT1 and HLT2

Integrated $J/\Psi$ trigger efficiency

Apply $J/\Psi$ map to harder $B_s$ spectrum

\[ \varepsilon_{J/\Psi}^{L0\times HLT1 \times HLT2} = 82\% \]
\[ \varepsilon_{B_s \rightarrow \mu \mu}^{L0\times HLT1 \times HLT2} = 86\% \]
The fraction of efficiencies (trigger, reconstruction, selection, PID...) needs to be computed/cancelled.

Reconstruction/acceptance:
- Ratio 4/3 body allows to evaluate with data the ratio 3/2 body
  
  Extra track effect: (acceptance + tracking)

\[
\frac{\varepsilon_{2\text{body}}^{\text{rec}}}{\varepsilon_{3\text{body}}^{\text{rec}}} \approx \frac{\varepsilon_{3\text{body}}^{\text{rec}}}{\varepsilon_{4\text{body}}^{\text{rec}}} = 0.58 \pm 0.04 \quad (\text{stat only})
\]
First results
How do we extract a limit?

- For each bin we need to know:
  1) Number of **expected signal** events (for a given BR & Lumi) and the number of **expected background** events (for a given Lumi)
  2) The number of **observed** events from data (blinded until January!)

- For **expected limit** we generate toy experiments from signal and background expectations.
No $B_s \rightarrow \mu\mu$ data from blinded region used. But all the pdfs (signal and background mass and GL) obtained from data, no MC.

- **Expected 90% exclusion sensitivity**

Current status of the analysis (without opening of “the box”)

Work ongoing to improve the GL  
→ **improve sensitivity!**

Plot presented by **Diego Martínez (USC)** at last LHCb plenary meeting!
Conclusions
Conclusions

- $BR(B_s \rightarrow \mu \mu)$ can constraint several NP models.
  - Value allowed from current experimental upper limit to below SM prediction.

- Analysis in LHCb based in a 3D (Geometrical Likelihood, Invariant Mass and Particle Identification) space.

- Calibration of Invariant mass and Geometrical Likelihood needed to determine the fraction of signal in each bin. Normalization to control channels used to calculate $BR$.

- LHCb working really fine. Data approaching MC in momentum and mass resolution, IP, and PID.

- Experimental limit by LHCb close to current’s world best at the end of this year. Hope to overtake it soon!
Backup
Maximal CP Violating Minimal Flavour Violation: Enhancements up to current upper limit, but also $< \text{SM}$ depending on the phases.

**CMSSM**: departures from SM possible, but less likely taking into account current experimental constraints.
New Physics effects (II)


NUHM1