Observation of $B^0_s \rightarrow \mu^+ \mu^-$
at CMS and LHCb and future plans

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Outline

• Motivation for the search for $B^0_{(s)} \rightarrow \mu^+ \mu^-$
• Results from CMS and LHCb combination
• Prospects for LHC Run 2 at LHCb
• Measuring the $B^0_s \rightarrow \mu^+ \mu^-$ effective lifetime
Motivation for $B^0_{(s)} \rightarrow \mu^+ \mu^-$

Highly suppressed decay in the SM:

- flavour changing neutral current
- helicity suppressed
- proceeds via $Z^0$ penguin and W-box diagrams

In the SM the effective Branching Fraction is

$$\mathcal{B}(B^0_q \rightarrow \mu^+ \mu^-)_{SM} \propto \frac{m^2_\mu}{M^2_{B^0_q}} |V_{tq}V^*_{tq}|^2 |C_{10}|^2$$

New Physics models can enhance this through (pseudo-)scalar contributions

$$\mathcal{B}(B^0_q \rightarrow \mu^+ \mu^-) \propto |V_{tq}V^*_{tq}|^2 \left( |S|^2 + |P^2 + \frac{m^2_\mu}{M^2_{B^0_q}} (C_{10} + C^{NP}_{10})|^2 \right)$$
Motivation for $B^0_{(s)} \rightarrow \mu^+ \mu^-$

- Aim is to measure the Branching Fraction to search for new physics
- Latest theoretical prediction for the time-integrated Branching Fractions
  
  $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9}$
  
  $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$
  

- $B^0$ mode further suppressed due to CKM matrix contributions

- The main contributors to the uncertainties are from the CKM matrix elements and $f_s$ and $f_d$ parameters.
Motivation for $B^0(s) \rightarrow \mu^+ \mu^-$

- The ratio of the Branching Fractions for each mode is another interesting variable.

- It is a powerful discriminate for NP models particularly the Minimal Flavour Violation Hypothesis.

- Precisely predicted in by the SM.

\[
\mathcal{R} = \frac{\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-)} = 0.0295^{+0.0028}_{-0.0025}
\]
CMS and LHCb combined measurement

• Combination of the full Run 1 data sets from CMS and LHCb. [Nature 522, 68, 2015]

• The analysis strategy follows closely the independent papers on Run 1 data for CMS and LHCb published in 2013. [PRL 111 (2013) 101805] [PRL 111 (2013) 101804]
The Experiments

Characteristics that make CMS and LHCb sensitive to $B_{(s)}^0 \rightarrow \mu^+ \mu^-$

- good PID for muons
- excellent triggers for muons and B-hadrons
- excellent primary vertex resolution
- good dimuon resolution; 32-75 MeV/c$^2$ for CMS and 25 MeV/c$^2$ for LHCb
The Data Set

- Run 1 data set consists of collisions at 7 TeV in 2011 and 8 TeV in 2012.
- The total integrated luminosity is 25 fb\(^{-1}\) for CMS and 3 fb\(^{-1}\) for LHCb.
- CMS operates at a higher luminosity but is less efficient at reconstructing low mass particles that LHCb.
  
  
  \[
  B_{(s)}^{0} \rightarrow \mu^+ \mu^-
  \]
  
  sensitivity of both experiments for \( B_{(s)}^{0} \rightarrow \mu^+ \mu^- \) is comparable.
Analysis strategy

CMS and LHCb data sets are selected separately with similar analysis strategies and a combined log-likelihood fit combines the data sets.

Similar analysis strategies

• soft preselection

• multivariate classifier, BDT - aimed at removing combinatorial background

• fit invariant mass distribution in bins of BDT output; 12 bins for CMS, 8 for LHCb

• normalise to $B^+ \rightarrow J/\psi K^+$ (and LHCb uses $B^0 \rightarrow K^+ \pi^-$ as well)
The data sets are combined by performing a simultaneous unbinned extended maximum likelihood fit to the dimuon mass spectrum in the BDT categories.

Backgrounds modelled in the fit; combinatorial background and exclusive backgrounds \((B^0 \rightarrow \pi^- \mu^+ \nu_\mu, B^0_s \rightarrow K^- \mu^+ \nu_\mu, \Lambda_b \rightarrow p \mu^- \nu_\mu, B^{0(+)} \rightarrow \pi^{0(+)} \mu^+ \mu^-, B \rightarrow h^+ h^-)\).

Parameters shared to in the fit:

- branching fraction of the \(B^0\) and \(B^0_s\)
- \(f_s\) and \(f_d\) - the \(B^0_s\) and \(B^0\) fragmentation fractions
- the branching fraction of \(B^+ \rightarrow J/\psi K^+\)
- exclusive backgrounds branching fractions

These account for corrections for the datasets and leads to the highest precision.
Results

Results from simultaneous fit;
\[ \mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9} \]
\[ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10} \]

Statistical significance from Wilks' theorem;
• 6.2 \sigma for \( B^0_s \rightarrow \mu^+ \mu^- \)

Statistical significance of \( B^0 \) mode checked using Feldman-Cousins approach.
• 3.0 \sigma for \( B^0 \rightarrow \mu^+ \mu^- \)
Results

• Fit and likelihood scans preformed for the ratio of the branching fractions with their SM predictions

\[ S_{SM}^{B_0(s)} = \frac{\mathcal{B}(B_0(s) \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B_0(s) \rightarrow \mu^+ \mu^-)} \]

• Result from the fit

\[ S_{SM}^{B_0} = 0.76^{+0.20}_{-0.18} \]

\[ S_{SM}^{B_0} = 3.7^{+1.6}_{-1.4} \]

• Compatibility with SM; 1.2 \( \sigma \) for \( B^0_s \) and 2.2 \( \sigma \) for \( B^0 \).
Results

- Fit and likelihood scans performed for the ratio of $B^0$ and $B^0_s$ branching fractions

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)}{\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-)}$$

- Result from the fit

$$\mathcal{R} = 0.14^{+0.06}_{-0.08}$$

- 2.3 $\sigma$ away from the SM and MFV value, including theoretical uncertainty.

[Nature 522, 68, 2015]
The Future for LHCb

- Precision of 25% for $B^0_s$ and 38% for $B^0$ leaves room for New Physics

- $B^0_s \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$ are still interesting for Run 2

- LHCb upgrade during LS2 will increase the available precision - much larger data set

- New observables will become accessible, notably the $B^0_s \rightarrow \mu^+ \mu^-$ effective lifetime
Effective Lifetime

- In the SM only the heavy $B^0_s$ mass eigenstate can decay as $B^0_s \to \mu^+ \mu^-$

- In general this gives a new interesting observable

\[
\langle \Gamma(B^0_s(t) \to f) \rangle \equiv \Gamma(B^0_s(t) \to f) + \Gamma(\bar{B}^0_s(t) \to f) \\
\propto e^{-t/\tau_{B_s}} [\cosh(y_s t/\tau_{B_s}) + A_{\Delta\Gamma} \sinh(y_s t/\tau_{B_s})]
\]

- The asymmetry rate is sensitive to the effective lifetime

\[
A_{\Delta\Gamma}^{\mu\mu} = \frac{1}{y_s} \left[ \frac{(1 - y_s^2) \tau_{\mu\mu} - (1 + y_s^2) \tau_{B_s}}{2\tau_{B_s} - (1 - y_s^2) \tau_{\mu\mu}} \right]
\]

- The effective lifetime can be measured from the same untagged events as the branching fraction
• $A_{\Delta r}$ is sensitive to New Physics independently of the Branching Fraction, particularly (pseudo-)scalar contributions.

• After LHCb upgrade and in high luminosity LHC era, LHCb could achieve a uncertainty of 5% for 46 fb$^{-1}$ on the effective lifetime.
Summary

Combined analysis for CMS and LHCb Run 1 data

• first observation of $B^0_s \rightarrow \mu^+ \mu^-$ at 6.2 $\sigma$.

• first evidence for $B^0 \rightarrow \mu^+ \mu^-$ at 3.0 $\sigma$.

• branching fraction results consistent with the SM

Looking to the future;

• precision of 25% for $B^0_s$ and 38% for $B^0$ leaves room for New Physics

• greater precision after the LHCb upgrade opens the doors for studying the $B^0_s \rightarrow \mu^+ \mu^-$ effective lifetime