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

Hannah Evans on behalf of the LHCb Collaboration

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UNIVERSITY OF CAMBRIDGE

LHCb

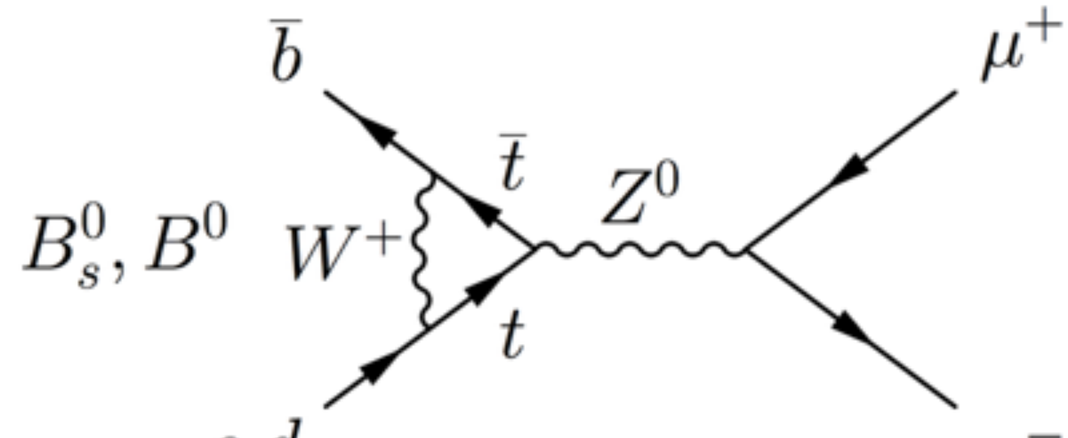
Outline

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

Motivation for $B^0_{(s)} \to \mu^+ \mu^-$

Highly suppressed decay in the SM:

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



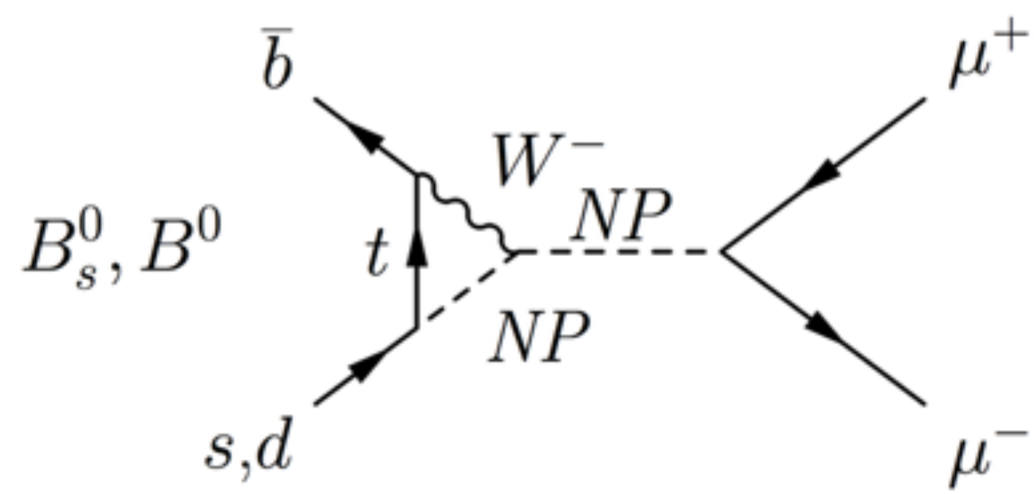
SM Z^0-penguin

In the SM the effective Branching Fraction is

$$\mathcal{B}(B_q^0 \to \mu^+\mu^-)_{SM} \propto \frac{m_\mu^2}{M_{B_q^0}^2} \left|V_{tq}V_{tq}^*\right|^2 \left|\mathcal{C}_{10}\right|^2$$

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

$$\mathcal{B}(B_q^0 \to \mu^+\mu^-) \propto \left|V_{tq}V_{tq}^*\right|^2 \left(|\mathcal{S}|^2 + \left|\mathcal{P}^2 + \frac{m_\mu}{M_{B_q^0}}(\mathcal{C}_{10} + \mathcal{C}_{10}^{NP})\right|^2 \right)$$



Beyond the SM penguin

Motivation for $B^0_{(s)} \to \mu^+ \mu^-$

- Aim is to measure the Branching Fraction to search for new physics

- Latest theoretical prediction for the time-integrated Branching Fractions

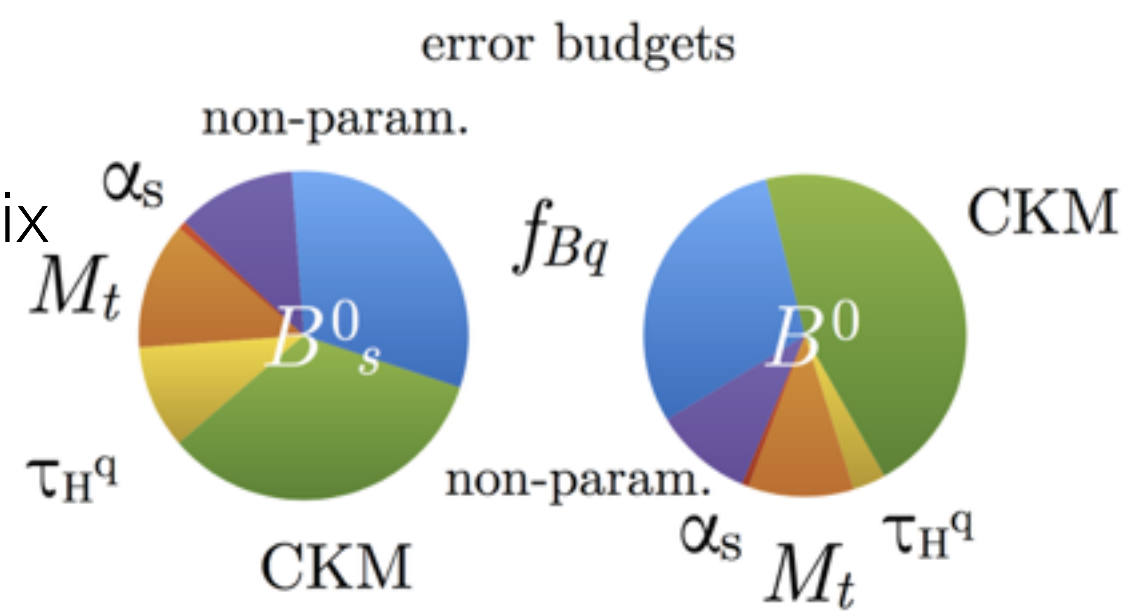
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$ [PRL 112 (2014) 101801]

updated with latest top quark measurement [arXiv:1403.4427 [hep-ex]]

- 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.



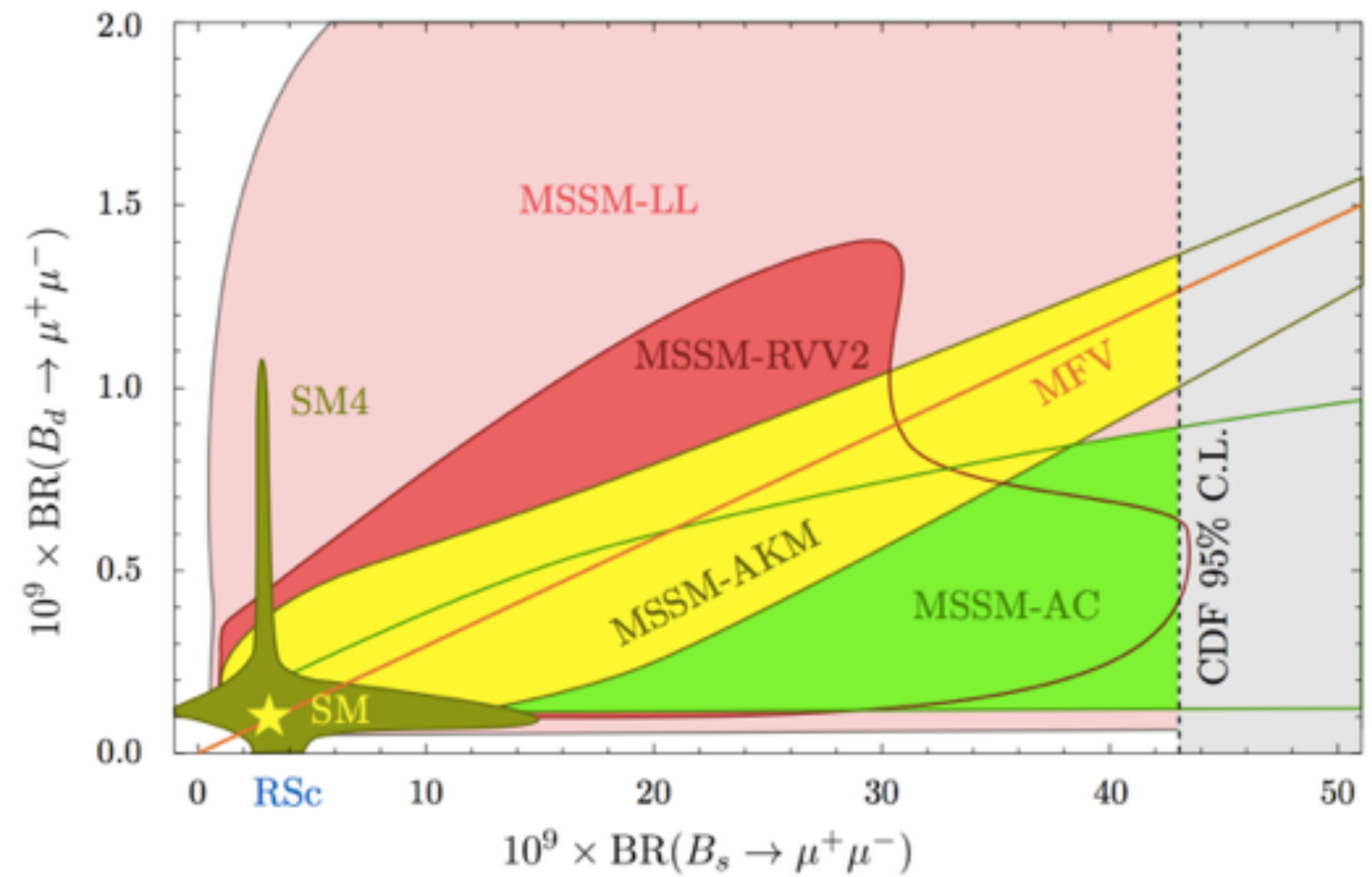
Motivation for $B^0_{(s)} \rightarrow \mu^+ \mu^-$

[arXiv:1012.3893 [hep-ph]]

- 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.



$$\mathcal{R} = \frac{\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)}{\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-)} = 0.0295^{+0.0028}_{-0.0025}$$

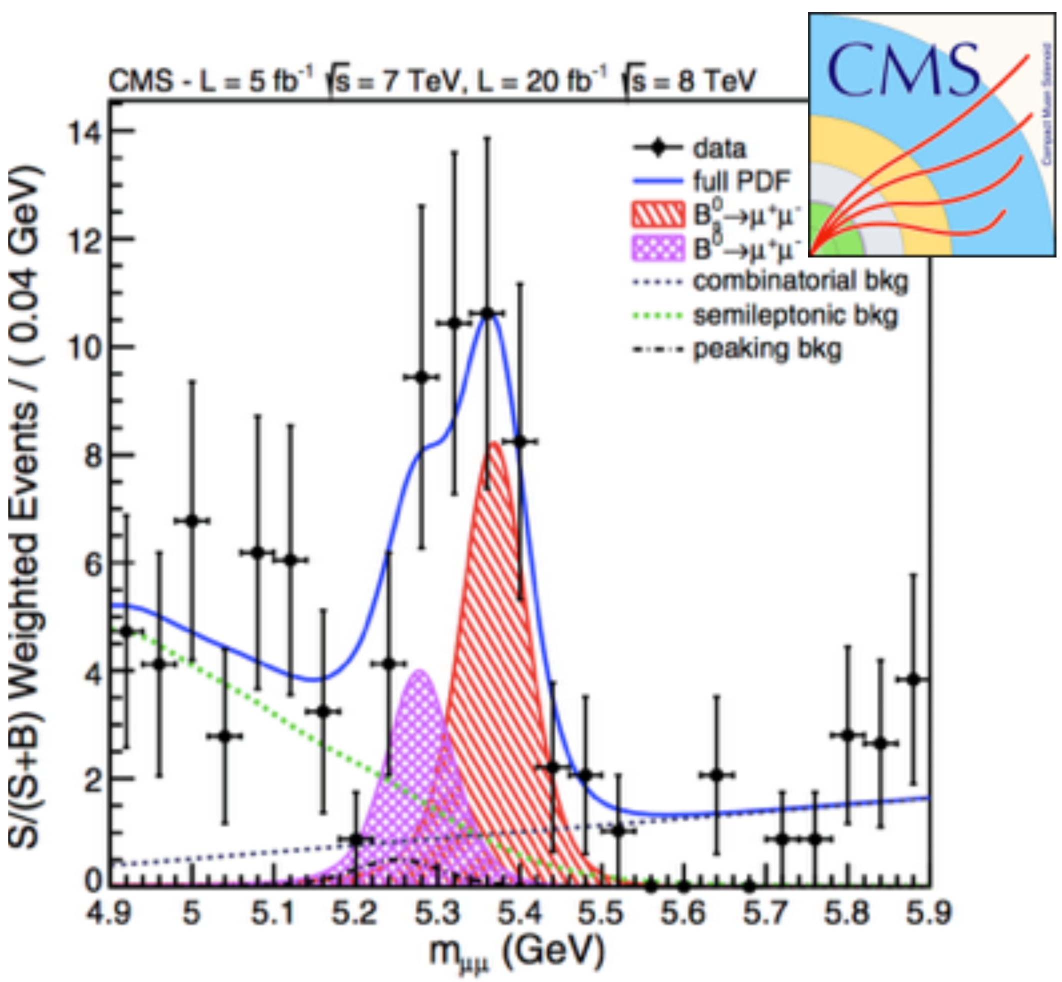
CMS and LHCb combined measurement

- Combination of the full Run 1 data sets from CMS and LHCb.

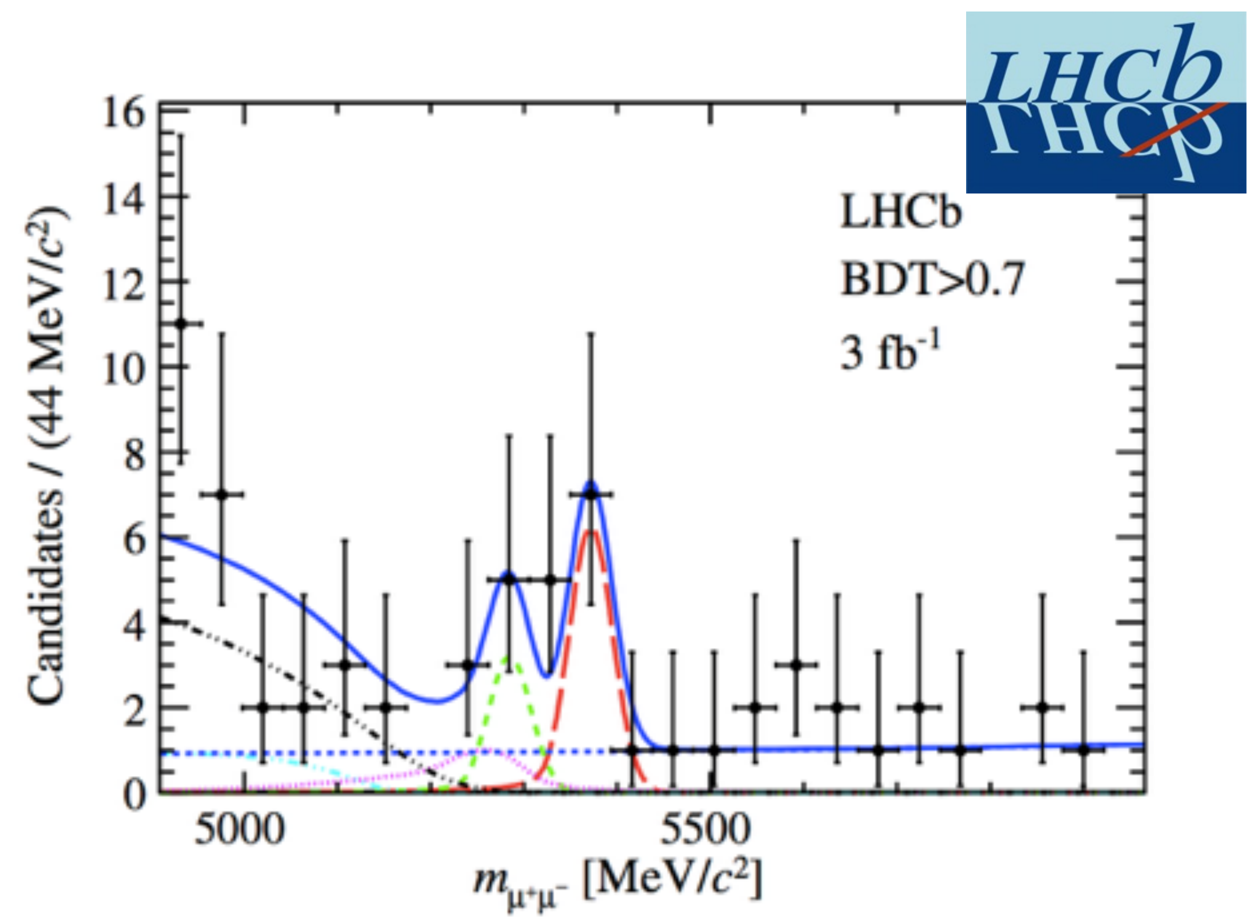
[Nature 522, 68, 2015]

- 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]

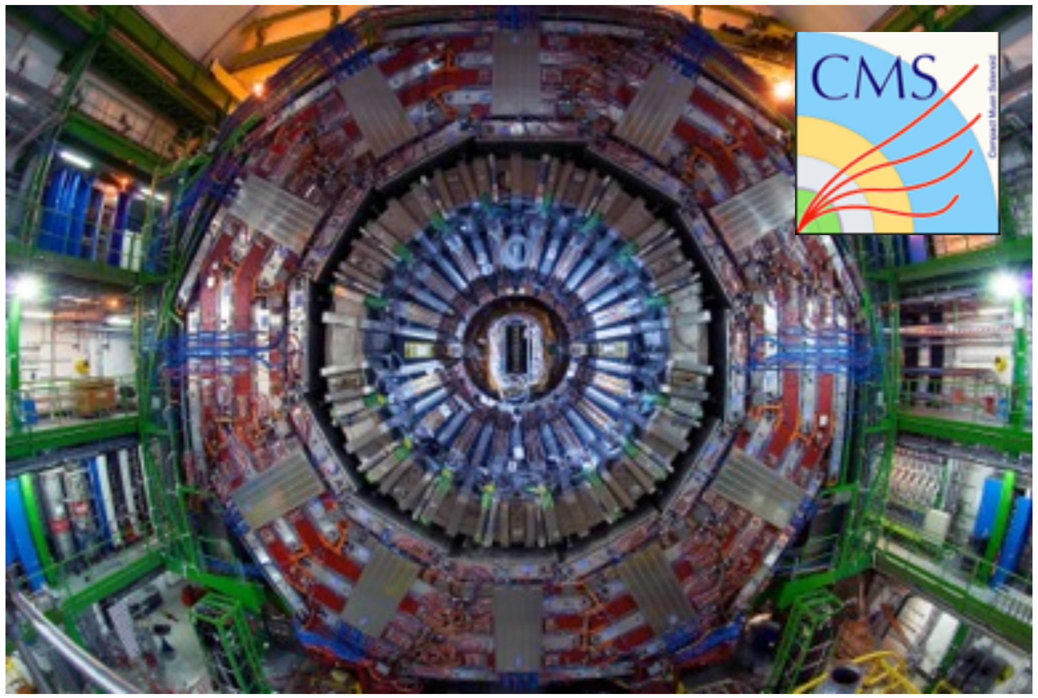


[PRL 111 (2013) 101804]



[PRL 111 (2013) 101805]

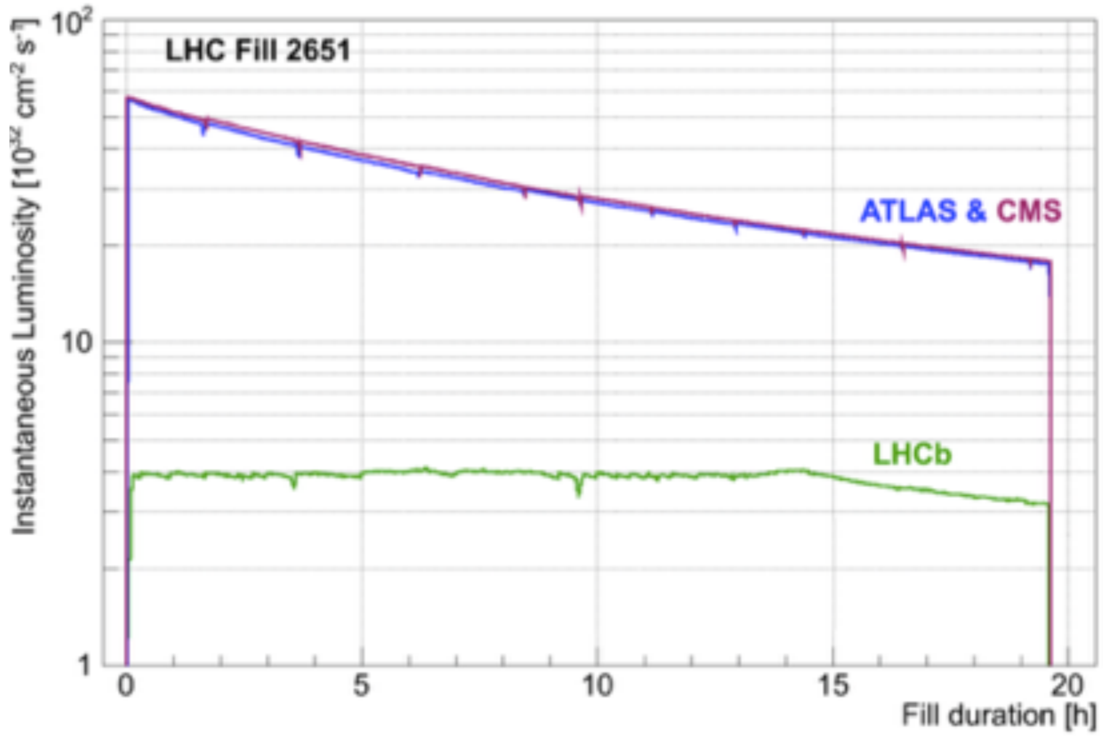
The Experiments



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

- 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
  $\longrightarrow$ sensitivity of both experiments for $B^0_{(s)} \rightarrow \mu^+ \mu^-$ 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)

Analysis strategy

- 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.

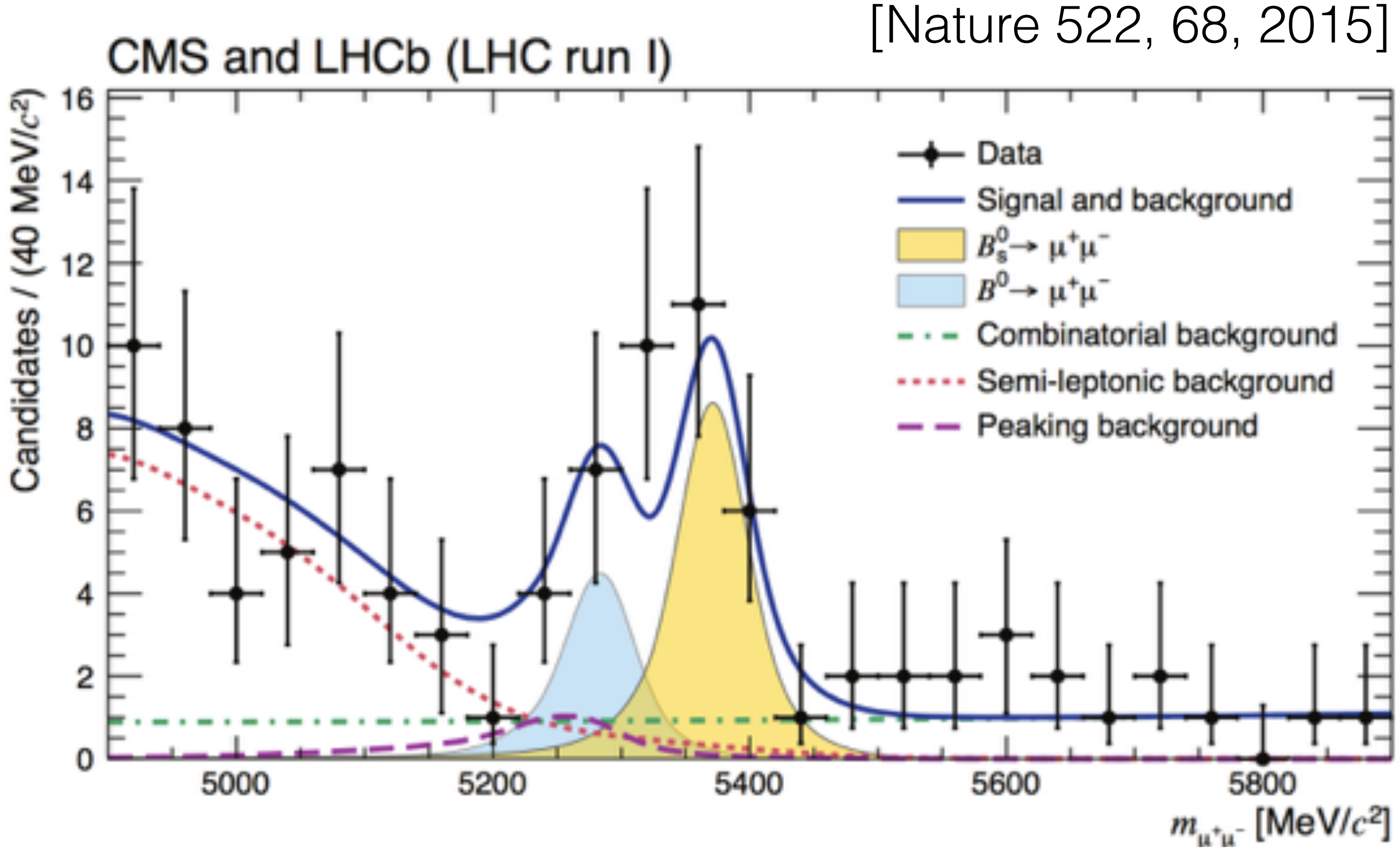
Results

[Nature 522, 68, 2015]

Results from simultaneous fit;

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$



Distribution of invariant mass for the six best BDT bins.

Statistical significance from Wilks' theorem;

- 6.2 σ for $B^0_s \to \mu^+ \mu^-$

Statistical significance of B^0 mode checked using Feldman-Cousins approach.

- 3.0 σ for $B^0 \to \mu^+ \mu^-$

Results

[Nature 522, 68, 2015]

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

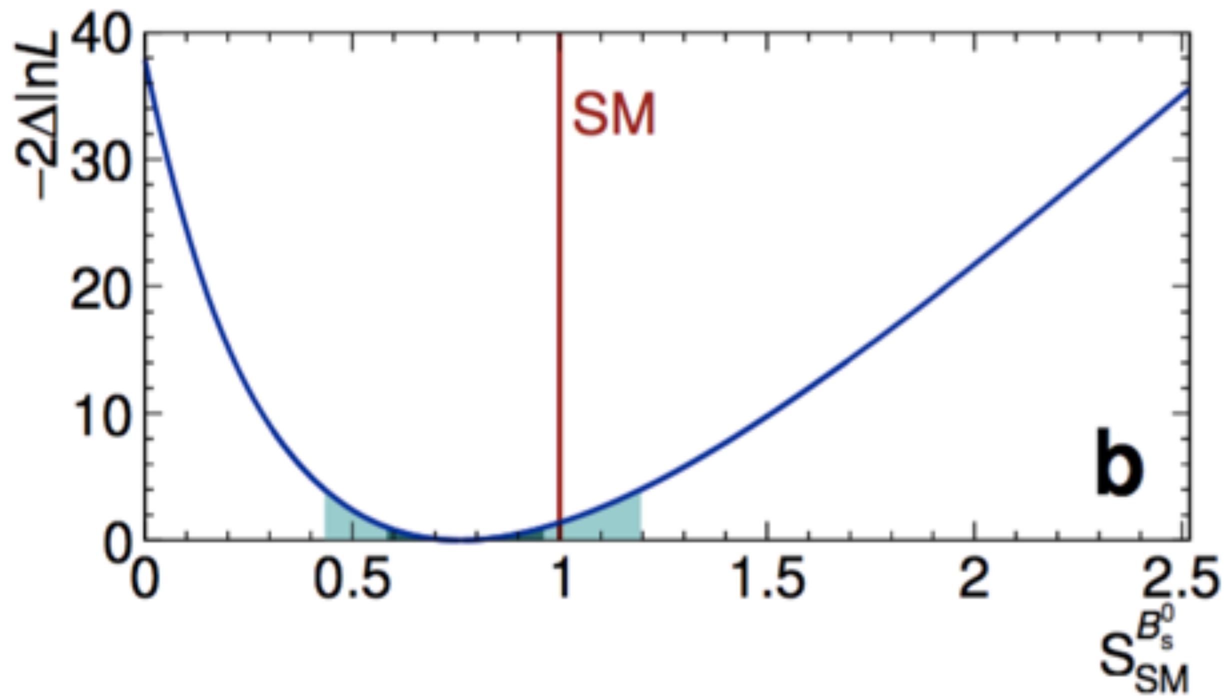
$$\mathcal{S}_{SM}^{B^0_{(s)}} = \frac{\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)}{\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)_{SM}}$$

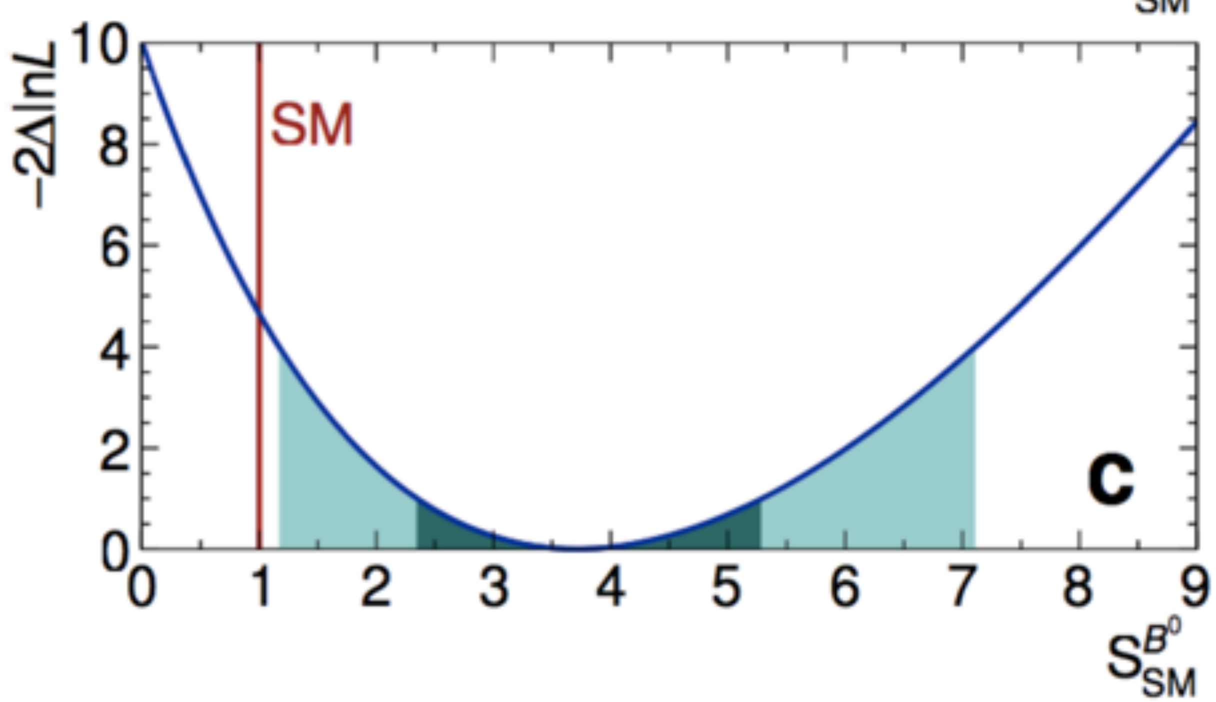
- Result from the fit

$$\mathcal{S}_{SM}^{B^0_s} = 0.76^{+0.20}_{-0.18}$$

$$\mathcal{S}_{SM}^{B^0} = 3.7^{+1.6}_{-1.4}$$

- Compatibility with SM; 1.2 σ for B^0_s and 2.2 σ for B^0.



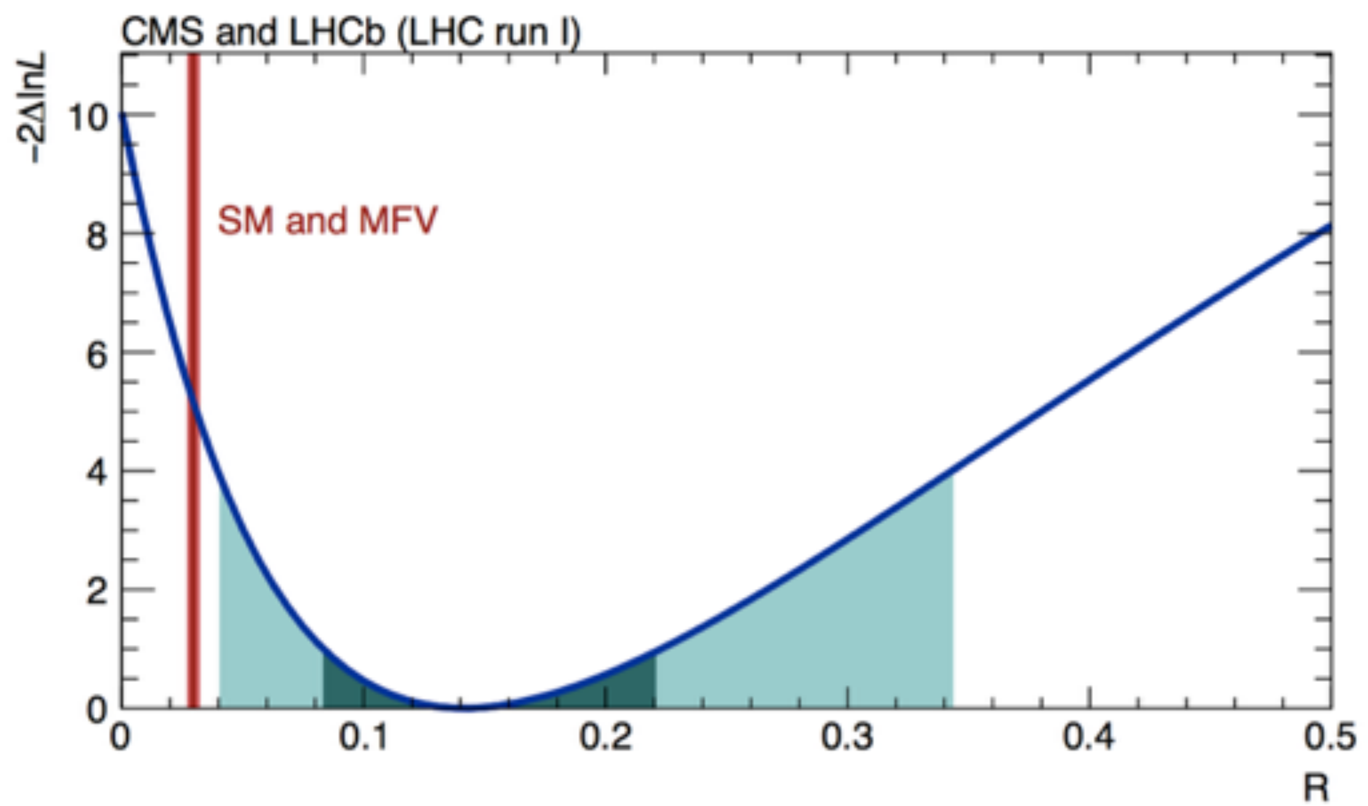


Results

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

[Nature 522, 68, 2015]

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



Variation of *-2ΔlnL* as a function of R.

- Result from the fit

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

- 2.3 σ away from the SM and MFV value, including theoretical uncertainty.

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

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

- The asymmetry rate is sensitive to the effective lifetime

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

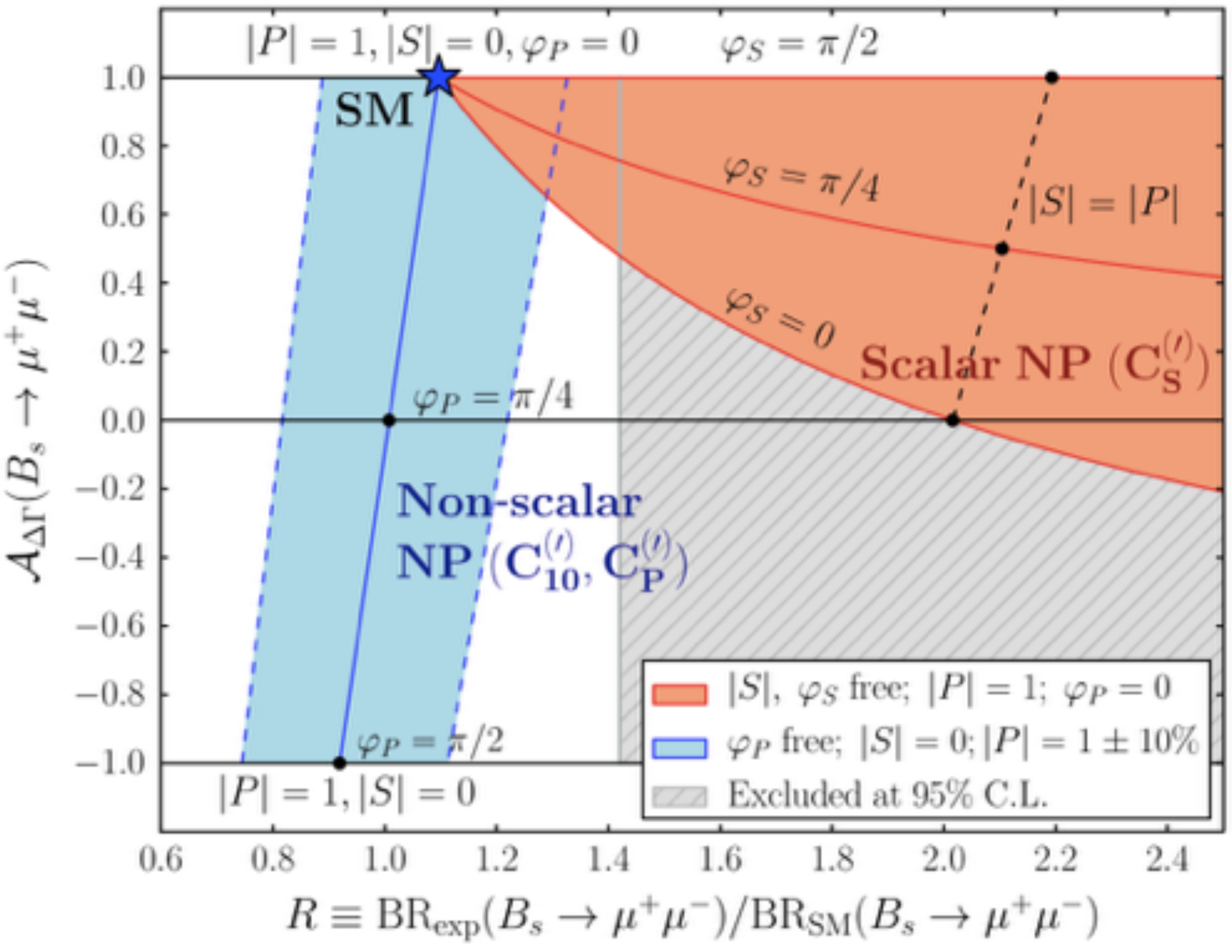
- The effective lifetime can be measured from the same untagged events as the branching fraction

Effective Lifetime

- $A_{\Delta\Gamma}$ 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.

[PRL 109 (2012) 041801]



Summary

Combined analysis for CMS and LHCb Run 1 data

- first observation of $B^0_s \rightarrow \mu^+ \mu^-$ at 6.2 σ.
- first evidence for $B^0 \rightarrow \mu^+ \mu^-$ at 3.0 σ.
- 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