Measurements of rare B meson decays properties with CMS Run2 data

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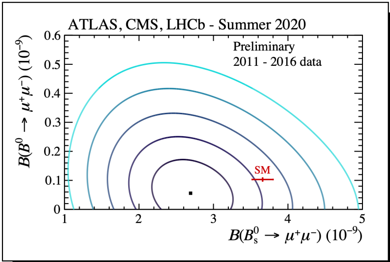
Introduction

Reporting results for $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ BF and lifetime measurements with CMS Run2 data.

- Rare $b \to s\ell^+\ell^-$ flavor changing neutral current decays
- Sensitive to BSM
- Theory clean and experimentally accessible.
- Non perturbative hadronic corrections through $B_{(s)}$
- **Both** Helicity suppressed by a factor m_μ^2 / m_B^2
- $B^0 \to \mu^+\mu^-$ CKM suppressed
- Deviations in Recent combined data analysis



Current Standard Model prediction:

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}.$$

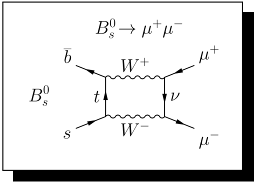
Introduction

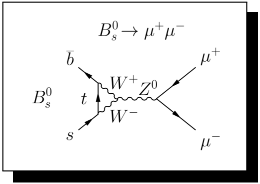
Importance of BF measurement:

- Proceed through **penguin** and **box** diagrams
- $b \to s\ell^+\ell^-$ decays dominated by semileptonic operators:
  - $O_9 = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)$
  - $O_{10} = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)$
- Fully leptonic final state depending mostly on O_{10}
- **BSM** physics as deviations from Wilson Coefficients (C_9 and C_{10})

Importance of lifetime measurement

- Two mass eigenstates heavy ($B^0_{s,H}$) and light ($B^0_{s,L}$)
- Mass eigenstates are also CP eigenstates
- Only $B^0_{s,H}$ decays to $\mu^+\mu^-$ final state (CP odd)
- **BSM** physics in deviation from SM estimated value for $\tau(B^0_s \to \mu^+\mu^-)$





Currently established lifetime value:
$\tau_H = 1.620 \pm 0.007$ ps

Data analysis overview

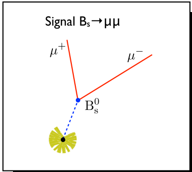
Strategy

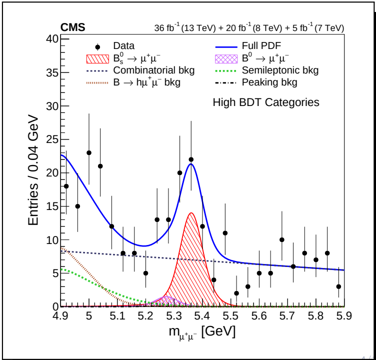
- Based on improved analysis technique with more data
- Searching for tow oppositely charged muons $\mu^+\mu^-$ and applying vertex fit
- Results extracted with Unbinned Maximum Likelihood fits **UML**
  - **BF:** 2D fit ($\mu\mu$ mas + mas uncertainty)
  - **Lifetime:** 3D fit ($\mu\mu$ mas + τ+ τuncertainty)

Data structure

16 categories:

- **4 data-taking periods:** 2016a, 2016b, 2017, 2018
- **2 η_F regions:** $0 < |\eta_F| < 0.7$ and $0.7 < |\eta_F| < 1.4$
- **2 signal purity regions:** from MVA_B discriminator
- **Integrated lumi:** 140 fb-1





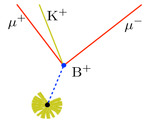
Data analysis overview

Background

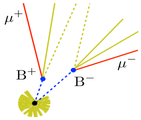
- **Partial:** from partially reconstructed 3 body decays.
- **Combinatorial:** $\mu\mu$ from different B mesons
- **Peaking:** charmless two-body decays leading to $\mu\mu$ misidentification
  - $B^0 \to K^+\pi^-$
  - $B^0_s \to K^+K^-$

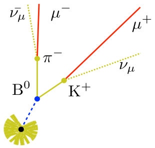
- MVA_B- combining multiple discriminating observables in a single powerful discriminator **(reducing Partial and Combinatorial)**
- MVA_μ- Tight muon identification **(reducing Peaking)**

3-body and partial decays



Combinatorial Background





Data analysis overview

Normalization channel

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \frac{\varepsilon_{B^+ \to J/\psi K^+}}{\varepsilon_{B_s^0 \to \mu^+\mu^-}} \frac{f_u}{f_s},$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \mathcal{B}(B_s^0 \to J/\psi\phi) \frac{N_{B_s^0 \to \mu^+\mu^-}}{N_{B_s^0 \to J/\psi\phi}} \frac{\varepsilon_{B_s^0 \to J/\psi\phi}}{\varepsilon_{B_s^0 \to \mu^+\mu^-}}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \frac{N_{B^0 \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \frac{\varepsilon_{B^+ \to J/\psi K^+}}{\varepsilon_{B^0 \to \mu^+\mu^-}} \frac{f_u}{f_d},$$

For Branching Fraction measurement we us other 2 B decay channels:

- $B^+ \to J/\psi K^+$ decay with $J/\psi \to \mu^+\mu^-$ is the preferred choice
- $B_s^0 \to J/\psi\phi$ decays with $\phi \to K^+K^-$ as an alternative

* (f_s/f_u $\mathcal{B}(B^+ \to J/\psi K^+)$ and $\mathcal{B}(B_s^0 \to J/\psi\phi)$ are external parameters to the analysis)

Event reconstruction and selection

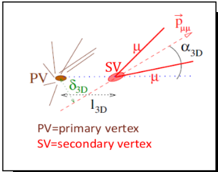
Event preselection

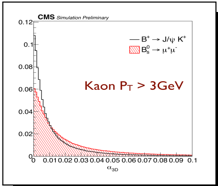
Selection	$B \to \mu^+\mu^-$	$B^+ \to J/\psi K^+$	$B^0_s \to J/\psi\phi$
B candidate mass [GeV]	[4.90, 5.90]	[4.90, 5.90]	[4.90, 5.90]
Blinding window [GeV]	[5.15, 5.50]		
$p_{T\mu}$ [GeV]	> 4	> 4	> 4
$\lvert\eta_\mu\rvert$	< 1.4	< 1.4	< 1.4
3D SV displacement significance	> 6	> 4	> 4
$p_{T\mu^+\mu^-}$ [GeV]	> 5	> 7	> 7
$\mu^+\mu^-$ SV probability	> 0.025	> 0.1	> 0.1
$\mu^+\mu^-$ invariant mass [GeV]		[2.9, 3.3]	[2.9, 3.3]
Kaon p_T [GeV]		> 1	> 1
Mass-constrained fit probability		> 0.025	> 0.025
2D $\mu^+\mu^-$ pointing angle [rad]		< 0.4	< 0.4
ϕ candidate mass [GeV]			[1.01, 1.03]

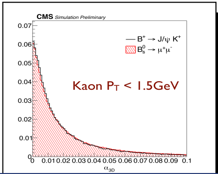
- **Selection requirements are as loose as possible**
  - Provide more data to MultiVariate Analysis (MVA)
  - Limited by trigger requirements
    - **L1:** required two high-quality oppositely charged muons with $\eta < 1.5$
    - **HLT:** high-quality secondary dimuon vertex was required and narrow mass windows around the B meson and J/ masses.
- **Normalization channel selection is optimized to match kinematics of signal**

Multivariate analysis

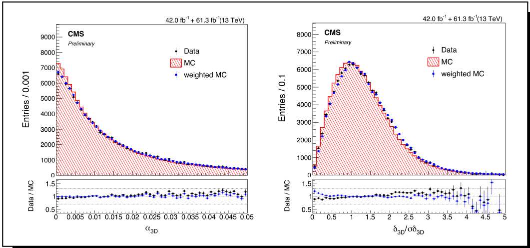
- **New multivariate analysis ($\mathbf{MVA_B}$) used to suppress the dominant backgrounds**
  Trained with signal MC and mass sideband data with the XGBoost package (advanced gradientboosting algorithm)
- **Most discriminating variables**
  - Pointing angles: α_{2D} , α_{3D}
  - Impact parameter and its significance: δ_{3D}, $\delta_{3D}/\sigma(\delta_{3D})$
  - Flight length and its significance: $l_{3D}/\sigma(l_{3D})$
  - Isolation for B candidate and muons
  - Dimuon vertex quality
- **MVA mismodeling can be a major source of systematics**
  Control sample from $B^+ \to J/\psi K^+$
- **MVA is trained to rejected $\mu\mu K$ events**
  - **Need to match $B^+ \to J/\psi K^+$ phase space to $B \to \mu^+\mu^-$**
  - **$\mu\mu K$:** pointing angle, impact parameter **(soft kaon)**
  - **$\mu\mu$:** vertex probability, displacement, isolation **(ignore kaon)**
  - Scaling flight length significance by 1.6







Multivariate analysis - XGBoost Reweighting



- Trained XGBoost classifier on MC vs Data with sWeights
- Capture the difference between MC and Data
- Use $w = (Prob_{Data})/(Prob_{M}C)$ as a weight to reweight $B \to \mu^+\mu^-$ MC samples

Method	Loose MVA_B selection			Tight MVA_B selection		
	2016	2017	2018	2016	2017	2018
Ratio	1.011 ± 0.013	0.939 ± 0.007	0.903 ± 0.008	1.058 ± 0.019	0.891 ± 0.008	0.885 ± 0.010
XGBoost	0.991 ± 0.008	0.949 ± 0.003	0.917 ± 0.002	1.008 ± 0.011	0.905 ± 0.004	0.908 ± 0.002

Branching fraction measurement Systematic uncertainty

Effect	$B^0_s \to \mu^+\mu^-$	$B^0 \to \mu^+\mu^-$
Trigger efficiency	2–4%	
Pileup	1%	
Vertex quality requirement	1%	
MVA_B correction	2–3%	
Tracking efficiency (per kaon)	2.3%	
$B^+ \to J/\psi K^+$ shape uncertainty	1%	
Fit bias	2.2%	4.5%
f_s/f_u ratio of the B meson production fractions	3.5%	-

- **Signal efficiency is correlated with the B s lifetime**
- $B \to \mu^+\mu^-$ branching fractions are measured assuming the SM lifetime value
- **Significant source of uncertainty is f_s/f_u**

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \mathcal{B}(B^+ \to J/\psi K^+) \frac{N_{B^0_s \to \mu^+\mu^-}}{N_{B^+ \to J/\psi K^+}} \frac{\varepsilon_{B^+ \to J/\psi K^+}}{\varepsilon_{B^0_s \to \mu^+\mu^-}} \frac{f_u}{f_s},$$

- Value used in this analysis **f_s/f_u = 0.23+/-0.008**
  - Based on P_t dependent results from LHCb PRD 104 (2021) 032005

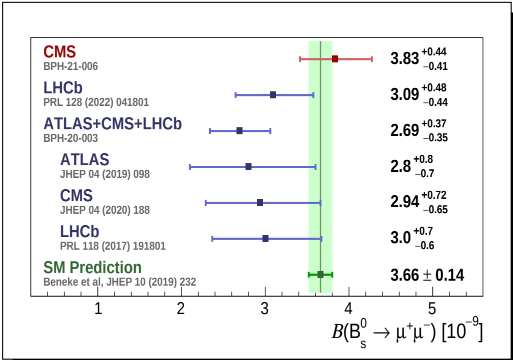
Lifetime measurement Systematic uncertainty

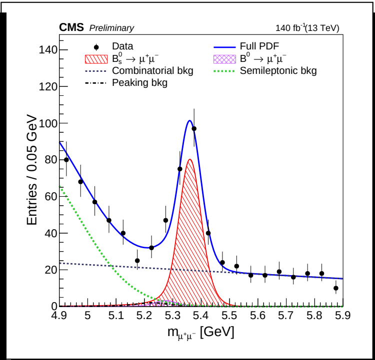
Effect	2016a	2016b	2017	2018
Efficiency modeling	0.01			
Lifetime dependence	0.01			
Decay time distribution mismodeling	0.10	0.06	0.02	0.02
Lifetime fit bias	0.04	0.04	0.05	0.04
Total	0.11	0.07	0.05	0.04

- **Dominant systematics comes from a strong correlation between MVA$_{\mathrm{B}}$ and decay time, which are hard to model well**
- Corrections can be derived in data and uncertainty is mostly limited by the size of the control sample

Results **Branching Fraction measurement**

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\ (\text{stat})\ ^{+0.19}_{-0.16}\ (\text{syst})\ ^{+0.14}_{-0.13}\ (f_s/f_u)\right] \times 10^{-9},$$





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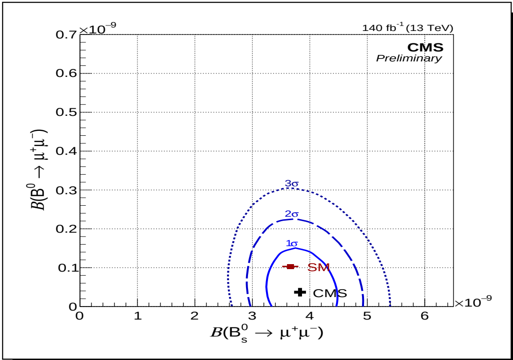
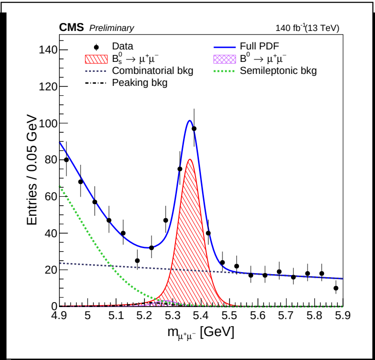
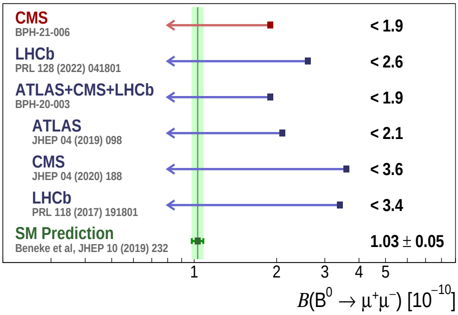
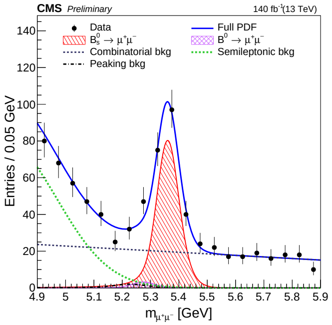




Results Branching Fraction measurement

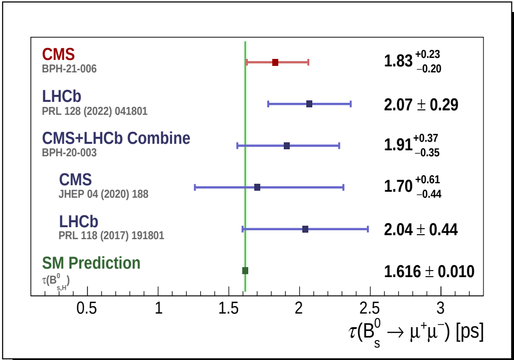
$$\mathcal{B}(\mathrm{B}^0 \to \mu^+\mu^-) = \left[0.37^{+0.75}_{-0.67}\ (\text{stat})\ ^{+0.08}_{-0.09}\ (\text{syst})\right] \times 10^{-10}$$

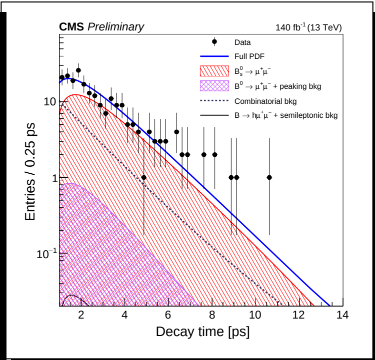




Results **Lifetime measurement**

$$\tau = 1.83\,^{+0.23}_{-0.20}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{syst})\text{ ps.}$$





Summary

- Measuring B meson decays properties gives unique chance for studies of new physics at the energy scales reachable to date.
- A measurement of B $\rightarrow \mu^+\mu^-$ Branching Fraction and searches for $B^0 \rightarrow \mu^+\mu^-$ have been performed
- Statistical uncertainty has been reduced to **11 %**
- Most precise measurement to date
- No evidence for $B^0 \rightarrow \mu^+\mu^-$ has been found