New CMS results on heavy flavour production and flavour anomalies

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Outline

- Bottom quark hadronization fractions at hadron colliders
  - Measurements of hadronization fractions
  - Observations from LHC-b
  - Recent CMS measurements
    - J/ψ final states
    - Hadronic final states
- Flavour anomalies – results from CMS
  - $B_s^0 \to \mu^+\mu^-$ decay properties

Bottom Quark Hadronization Fractions

- Number of weakly decaying B hadrons reconstructed in an exclusive final state:

$$N_X = \sigma_b \cdot A \cdot f_q \cdot \mathcal{B}\left(B_q \to X\right) \cdot \epsilon_X$$

- Measured branching fractions (eg, for B_s^0):

$$\mathcal{B}(B_s^0 \to X) = \frac{N_X}{\sigma_b \cdot A \cdot f_s \cdot \epsilon_X}$$

- Ratio of branching fractions (eg, $B \to \mu^+\mu^-$):

$$\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-)}{\mathcal{B}(B_d^0 \to \mu^+\mu^-)} = \frac{N_{B_s \to \mu^+\mu^-}}{N_{B_d \to \mu^+\mu^-}} \cdot \frac{f_d}{f_s}$$

- Need to know hadronization fractions for precision measurements at hadron colliders

Bottom Quark Hadronization Fractions

- Assumed to be independent of environment, $p_T(B)$…

$$f_u + f_d + f_s + f_{\text{baryon}} = 1$$

- Measured at LEP ($\sqrt{s} = M_Z$) and the Tevatron

Quantity		Z decays	Tevatron
B^+ or B^0 fraction	$f_u = f_d$	0.407 ± 0.007	0.344 ± 0.021
B_s^0 fraction	f_s	0.101 ± 0.008	0.115 ± 0.013
b-baryon fraction	f_{baryon}	0.085 ± 0.011	0.198 ± 0.046
B_s^0/B^0 ratio	f_s/f_d	0.249 ± 0.023	0.334 ± 0.040

$\sim 2\,\sigma$

Eur. Phys. J. C (2021) 81:226

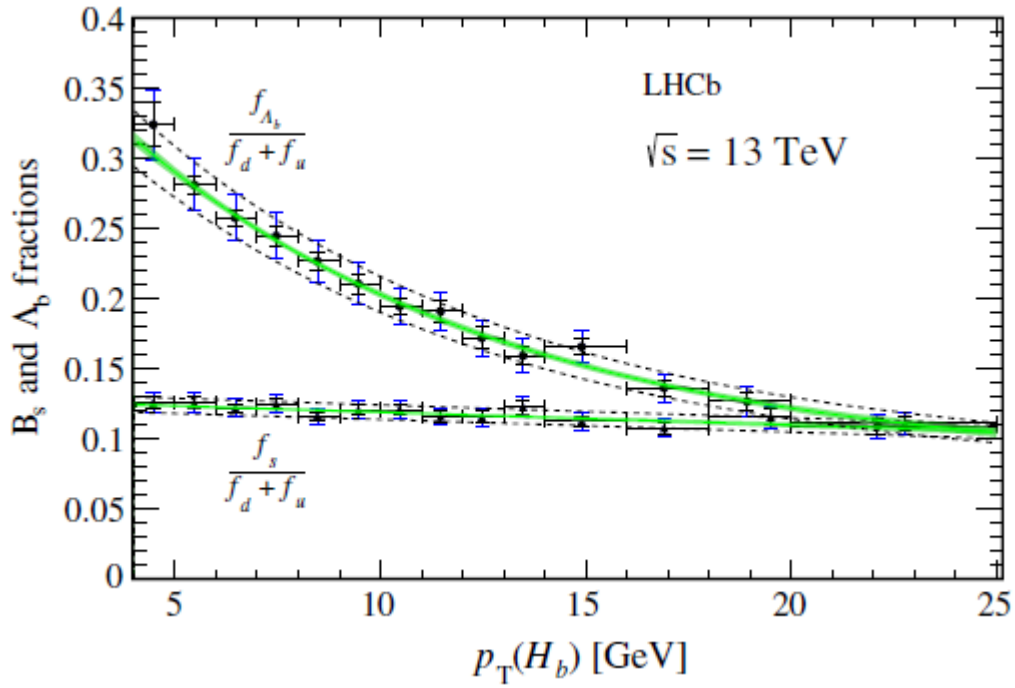
- Environmental influence is potentially an important systematic effect
  - Could limit precision B_s branching fraction measurements

Environmental Influence on Hadronization Fractions

- LHC-b observed significant $p_T(\Lambda_b)$ dependence
  - Weaker but significant dependence on $p_T(B_s)$

Inclusive semi-leptonic decays:

$$H_b \to H_c X \mu^- \bar{\nu}_\mu$$



Phys. Rev. D 100, 031102(R)

$$\frac{f_s}{f_u + f_d}(p_T) = A[p_1 + p_2 \times (p_T - \langle p_T \rangle)]$$

$$p_2 = (-0.91 \pm 0.25) \times 10^{-3}\ \text{GeV}^{-1}$$

New CMS Measurement of f_s/f_u

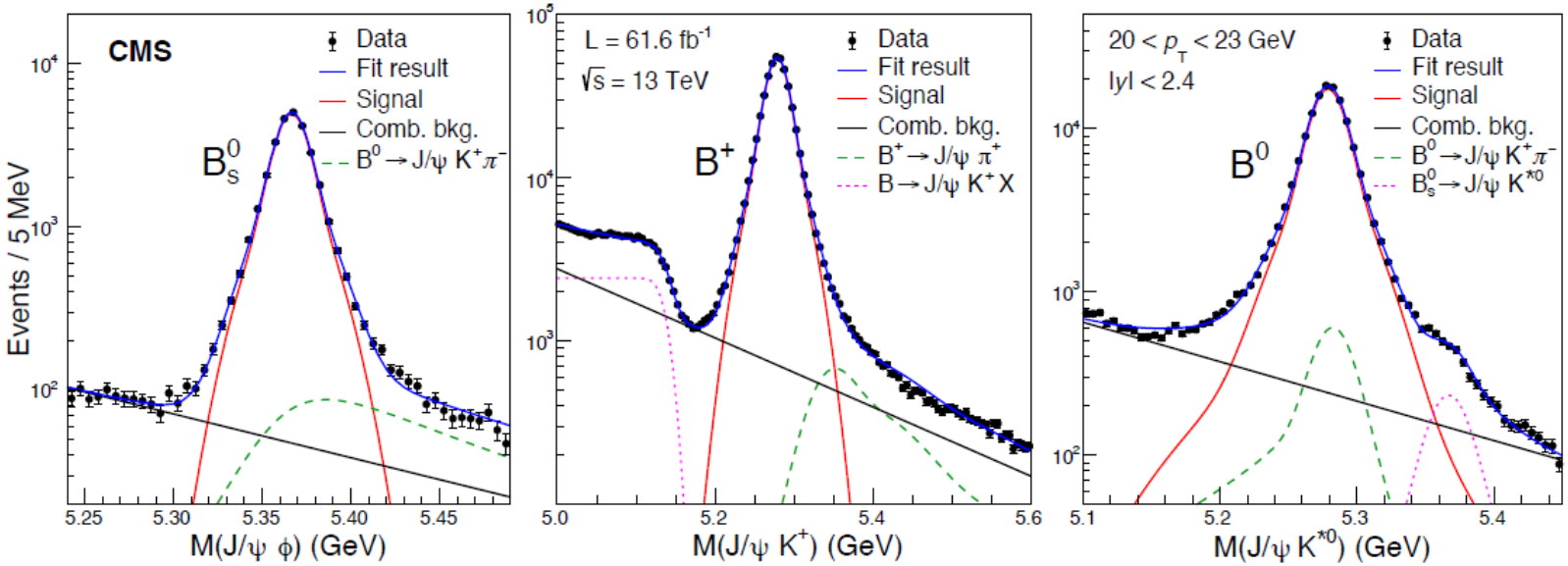
- pp collisions at $\sqrt{s} = 13\ \mathrm{TeV}$, $61.6\ \mathrm{fb}^{-1}$ collected in 2018
- Di-muon + track trigger:
  - $p_T(\mu^{\pm}) > 4\ \mathrm{GeV}, |\eta| < 2.5, m(\mu^+\mu^-)$ within $2.9 - 3.3\ \mathrm{GeV}$
  - $p_T(track) > 1.2\ \mathrm{GeV}, |\eta| < 2.4$
  - Displaced vertex requirement
- Offline reconstruction:
  - $B^+ \to J/\psi K^+$
  - $B^0 \to J/\psi K^{*0}, K^{*0} \to K^-\pi^+$
  - $B_s^0 \to J/\psi\phi, \phi \to K^+K^-$

Vertex fit quality cuts
$12 < p_T(B) < 70\ \mathrm{GeV}$
$|y| < 2.4$

arXiv:2212.02309

New CMS Measurement of f_s/f_u

Example: $20 < p_T < 23$ GeV



- Determined from fit:
  - Shape of combinatorial background
  - Shape of $B^+ \to J/\psi K^+ X$ component
- Constrained from Monte Carlo:
  - Cabibbo suppressed decay fraction
  - Swapped kaon/pion mass assignments

New CMS Measurement of f_s/f_u

- In principle,

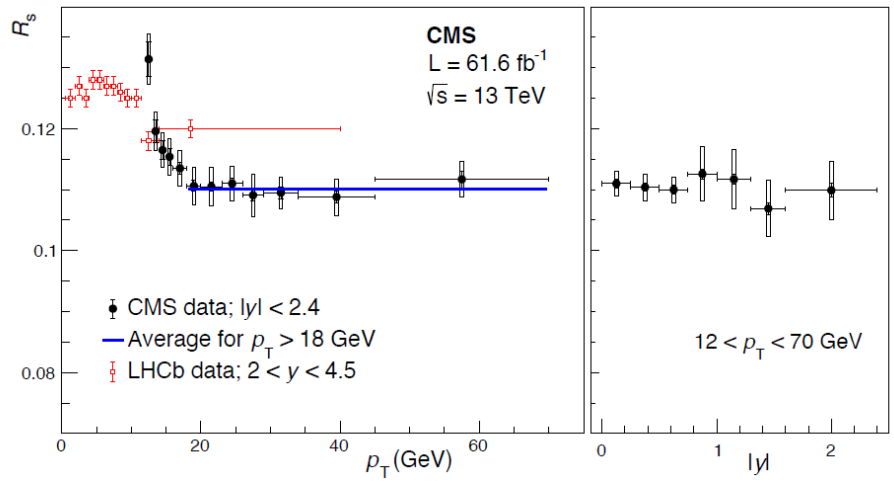
$$\frac{f_s}{f_u} = \frac{N_{B_s}}{N_{B^+}} \cdot \frac{\epsilon_{B^+}}{\epsilon_{B_s}} \cdot \frac{\mathcal{B}(B^+ \to J/\psi K^+)}{\mathcal{B}(B_s \to J/\psi\phi)\mathcal{B}(\phi \to K^+K^-)}$$

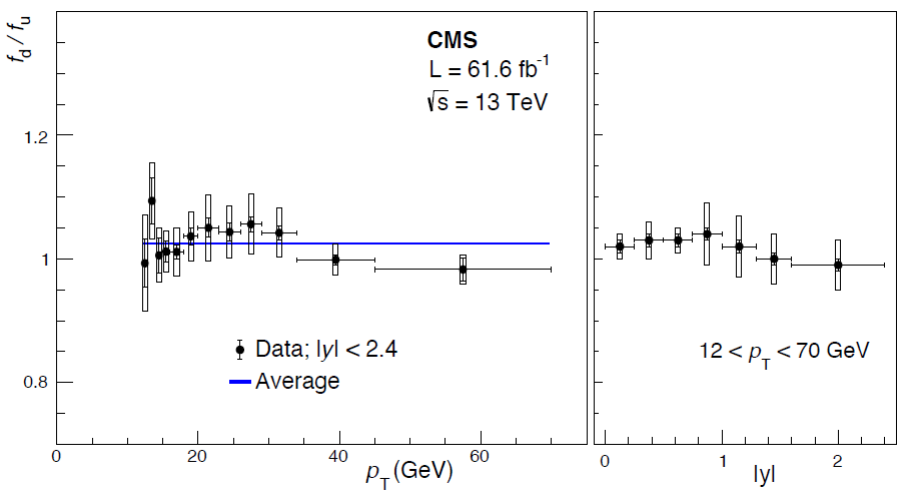
- Most branching fractions are measured precisely
- But $\mathcal{B}(B_s \to J/\psi\phi)$ is dominated by an LHC-b analysis that measures the p_T dependence of f_s/f_d
  - Phys. Rev. D 104, 032005 (August 2021)
- CMS chooses to report measurements of

$$\mathcal{R}_d = \frac{f_d}{f_u} \cdot \frac{\mathcal{B}(B^0 \to J/\psi\, K^{*0})\mathcal{B}(K^{*0} \to K^-\pi^+)}{\mathcal{B}(B^+ \to J/\psi\, K^+)}$$

$$\mathcal{R}_s = \frac{f_s}{f_u} \cdot \frac{\mathcal{B}(B_s^0 \to J/\psi\, \phi)\mathcal{B}(\phi \to K^+K^-)}{\mathcal{B}(B^+ \to J/\psi\, K^+)}$$

New CMS Measurement of f_s/f_u





- Matches LHC-b result at low p_T
- No significant dependence on rapidity
- Branching fractions for B^0 and B^+ are known precisely
- Compatible with unity $f_d/f_u = 1.015 \pm 0.051$
- $\mathcal{R}_s = 0.1102 \pm 0.0027$ for $p_T > 18$ GeV

Alternative CMS Analysis of f_s/f_u

- The ratio f_s/f_u could be determined if branching fractions were known precisely
- Reliable theoretical prediction for the ratio

$$\frac{\mathcal{B}(B_s^0 \to D_s^+\pi^-)}{\mathcal{B}(B^0 \to D^-h^+)} \sim \frac{\tau_{B_s}}{\tau_{B_d}} \left|\frac{V_{ud}}{V_{us}}\right|^2 \left(\frac{f_\pi}{f_K}\right)^2 \left[\frac{F_0^{(s)}(m_\pi^2)}{F_0^{(d)}(m_K^2)}\right]^2 \left|\frac{a_1(D_s\pi)}{a_1(D_dK)}\right|^2$$

Phys. Rev. D **82**, 034038 (2010)

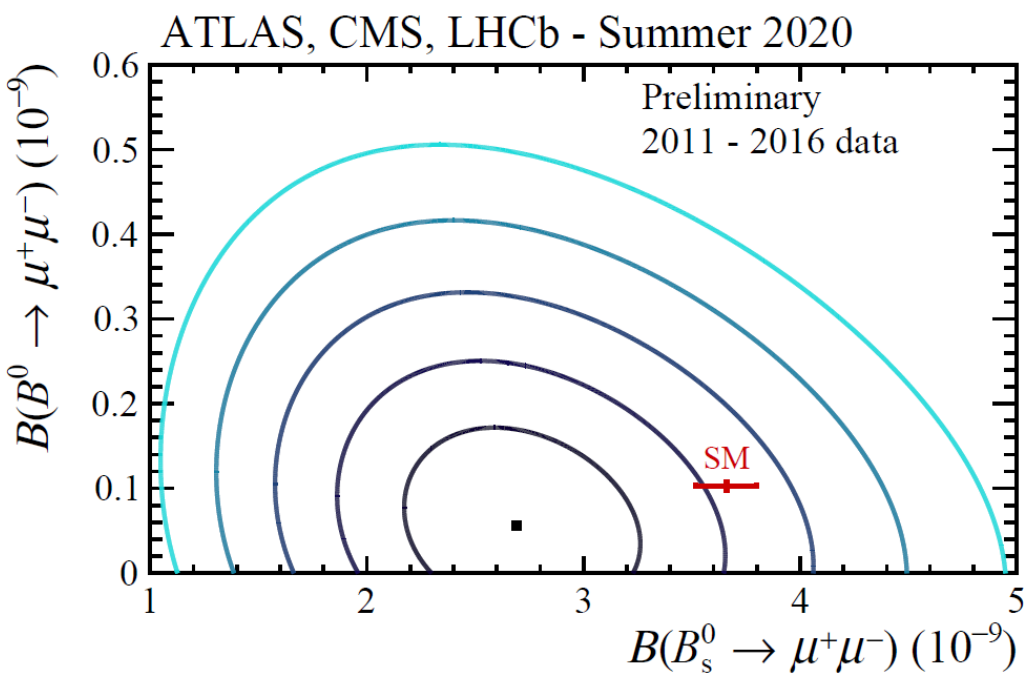
- Motivates reconstructing these decays in pp collisions
- The challenge is collecting these using a suitable trigger

B Parking at CMS

- Single muon trigger:
  - Minimum p_T requirement
  - Minimum signed impact parameter significance
  - Thresholds and pre-scales adjusted based on instantaneous luminosity to level the trigger rate
  - High level trigger rate < 5 kHz
- 10 billion events saved to tape and reconstructed when computing resources become available
- Opposite side jets provide an unbiased sample of b-decays
  - 60-90% purity estimated by reconstructing $B \rightarrow D^{*+}\mu^- \bar{\nu}_\mu$
- *Now possible to reconstruct fully hadronic B decays*

Flavour Anomalies at CMS

- 2020 Combination of ATLAS, LHCb, and CMS measurements of $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$
  - Di-muon mass spectra from each experiment
  - Correlated uncertainty in f_d/f_s from LHCb



  - Deviation from standard model is 2.1σ (2.4σ for just B_s^0)

$B_s^0 \to \mu^+\mu^-$ Decay Properties at CMS

- New measurement of $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ and B_s^0 lifetime (arXiv:2212.10311 to be published in PLB)
  - 140 fb^{-1} of pp collision data collected 2016-2018

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

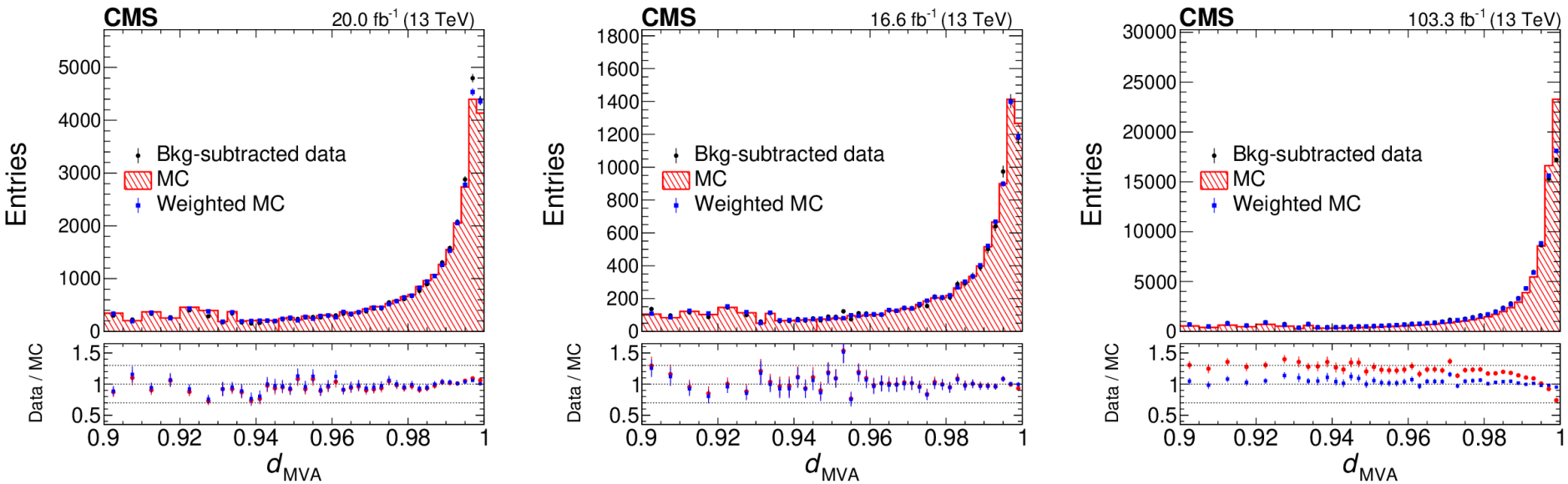
  - Normalization to $B_s^0 \to J/\psi\phi(1020)$ considered as a cross-check

$B_s^0 \to \mu^+\mu^-$ Decay Properties at CMS

- Event selection:
  - Di-muon trigger, $|\eta| < 1.5$, secondary vertex requirement, mass restrictions: 4.5-6.0 GeV and 2.9-3.3 GeV
  - Offline selection: tight muon ID, matched to high-quality inner track with $p_T > 4\ \mathrm{GeV}, |\eta| < 1.4$
  - Track requirements: $p_T > 1\ \mathrm{GeV}, |\eta| < 2.5$
- Backgrounds:
  - Semi-leptonic decays of two heavy quarks
  - Partially reconstructed semi-leptonic decays of B hadrons
  - Charmless two-body hadronic B decays ($B^0 \to K^+\pi^-, B_s^0 \to K^+K^-$)
- MVA discriminant:
  - Displaced secondary vertex geometry, pointing to primary vertex
  - Isolation requirements
  - Efficiency depends on B_s^0 lifetime

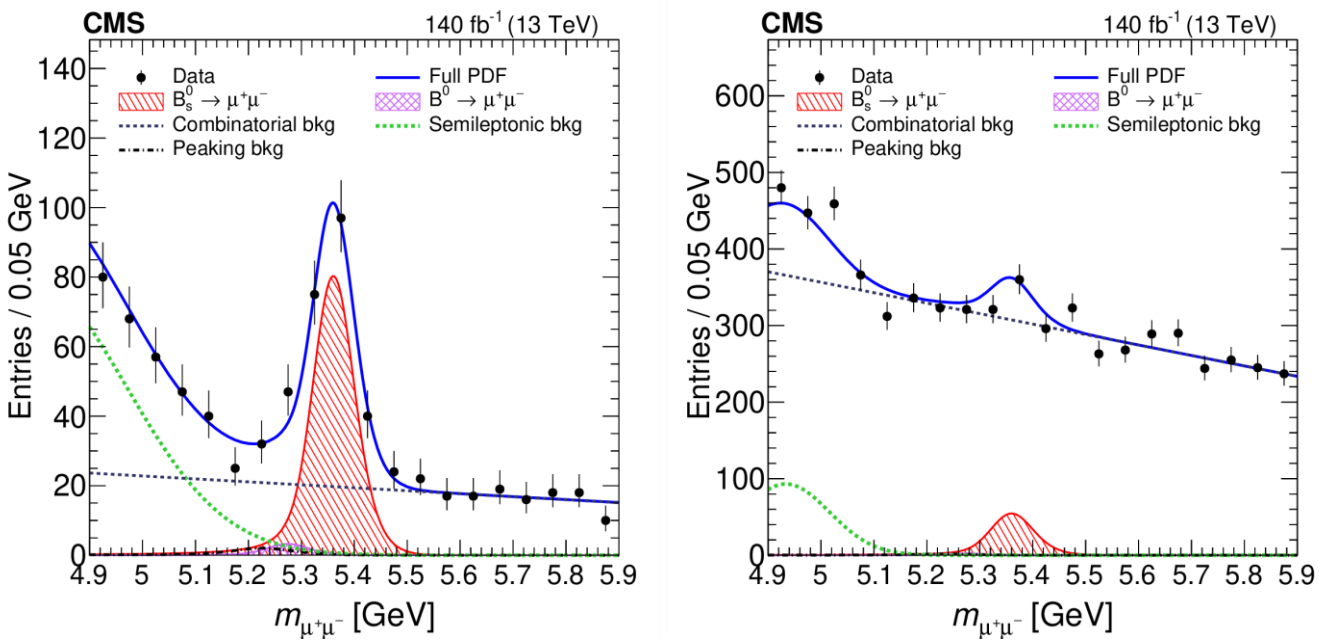
$B_s^0 \to \mu^+\mu^-$ Decay Properties at CMS

- MVA performance measured using $B^+ \to J/\psi K^+$
  - Control sample selected using $p_T(K^+) < 1.5\ \mathrm{GeV}$
  - Scale factor accounts for smaller $\mu^+\mu^-$ opening angle
  - Ratio of data/MC in $B^+ \to J/\psi K^+$ applied to $B_s^0 \to \mu^+\mu^-$
  - Weight factors for MC derived from XGBOOST classifier



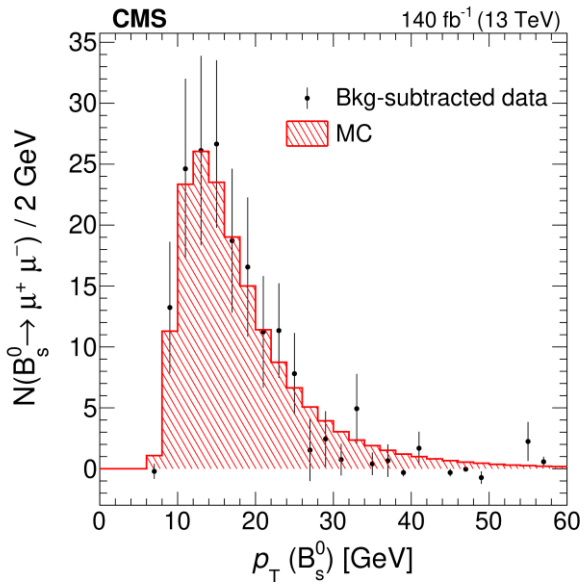
$B_s^0 \to \mu^+\mu^-$ Decay Properties at CMS

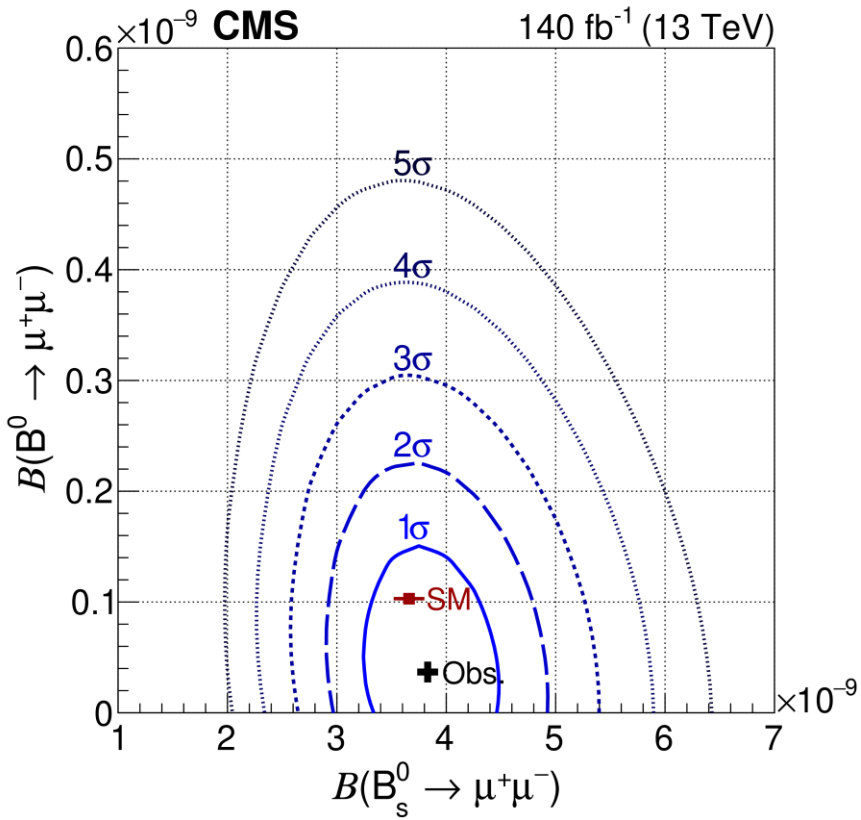
- Un-binned maximum likelihood fit:
  - B_s^0 and B^0 signal: crystal ball functions
  - Semi-leptonic decay background shape: simulations
  - Peaking $B \to h^+h^-$ background: simulation and measured BF's
  - Performed separately in 16 distinct categories (data taking period, MVA discriminant output, $|\eta|$ of forward muon)



$B_s^0 \to \mu^+\mu^-$ Decay Properties at CMS

- External inputs:
  - $\mathcal{B}(B^+ \to J/\psi\, K^+) = (1.020 \pm 0.019) \times 10^{-3}$
  - $\mathcal{B}(J/\psi \to \mu^+\mu^-) = (5.961 \pm 0.033) \times 10^{-2}$
  - $f_s/f_u = 0.231 \pm 0.008$ (from LHCb)





- Consistent with SM

$B_s^0 \to \mu^+\mu^-$ Decay Properties at CMS

- Results:
  - Normalized using $B^+ \to J/\psi K^+$

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

  - Normalized using $B_s^0 \to J/\psi\phi(1020)$

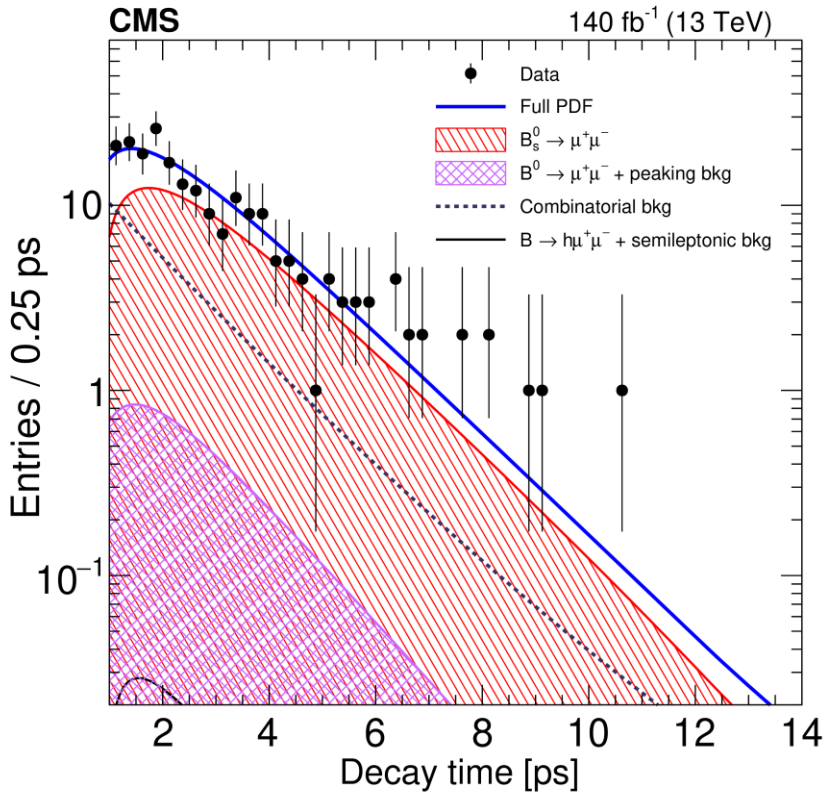
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left[4.02^{+0.40}_{-0.38}\,(\text{stat})^{+0.28}_{-0.23}\,(\text{syst})^{+0.18}_{-0.15}(\mathcal{B})\right] \times 10^{-9}$$

  - $B^0 \to \mu^+\mu^-$ branching fraction:

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

$B_s^0 \to \mu^+\mu^-$ Decay Properties at CMS

- Lifetime extracted from simultaneous fit to mass, decay time, decay time uncertainty



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

Summary

- Bottom quark hadronization fractions
  - CMS observes p_T dependence in f_s/f_u in agreement with LHCb
  - No variation with rapidity observed
  - Measures f_d/f_u compatible with unity as is typically assumed
  - Reduced dependence on unknown branching fractions may be possible with fully hadronic B decays
- $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ branching fractions:
  - Consistent with standard model
- Lifetime of $B_{s,H}^0$ eigenstate:

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

Backup Material

$B_s^0 \to \mu^+\mu^-$ Decay Properties at CMS

- MVA performance scale factors:

Method	$d_{\mathrm{MVA}} > 0.9$ selection			$d_{\mathrm{MVA}} > 0.99$ 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

$B_s^0 \to \mu^+\mu^-$ Systematic Uncertainties

- Branching fractions:

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

- Lifetimes:

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

Acknowledgements

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