Rare B decays at the LHC

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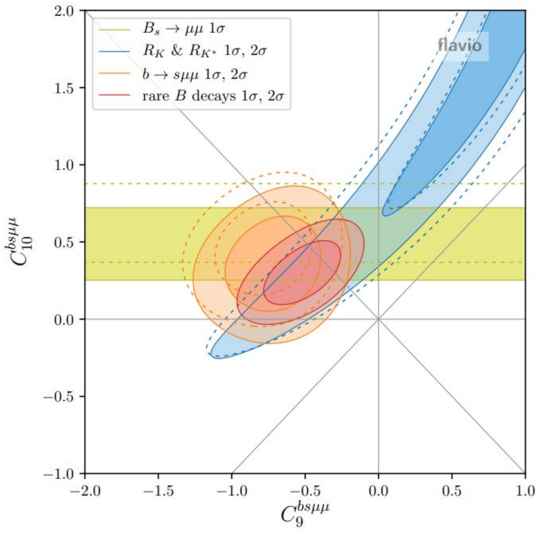
Introduction

Motivations

- Rare B decays are a powerful probe for exploring physics beyond the SM
- Unknown particles, too heavy to be directly produced at colliders, may lead to measurable deviations from the SM predictions

State-of-the-art

- As of today, multiple discrepancies are observed in rare B decays
  - ~3σ LFU violation in R(K) and R(K*)
  - ~2-3σ in branching fractions and angular observables
- Global fits provide a good description of data with the Wilson coefficients $C_{9,10}$
- **The CERN LHC is an excellent environment to study such processes**
  - High production cross section: σ(pp → $b\bar{b}$) ≈ 500 μb @ 13 TeV
    - $\approx 5 \cdot 10^{11} b\bar{b}$ pairs/fb^{-1}
  - One dedicated experiment: LHCb
  - Two general-purpose experiments with excellent B physics capabilities: ATLAS, CMS



From: Altmannshofer, Stangl [arXiv:2103.13370]

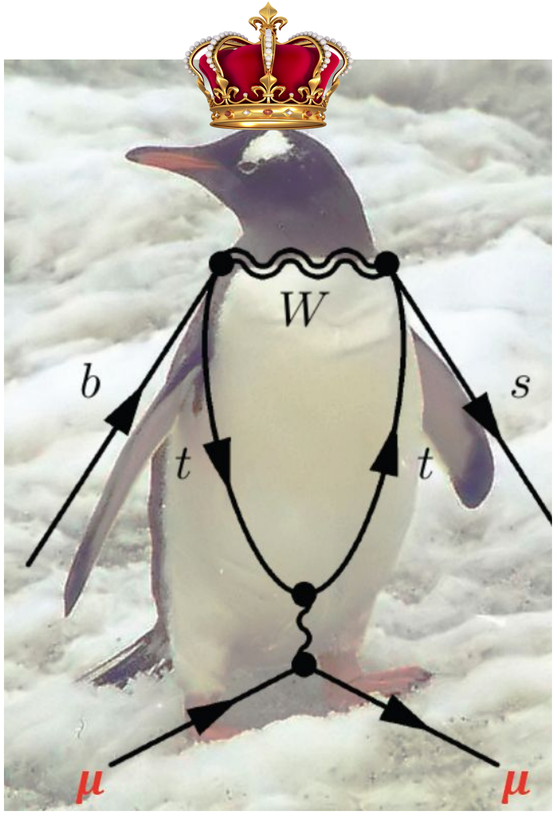
$$B_{(s)} \rightarrow \mu^+\mu^-$$

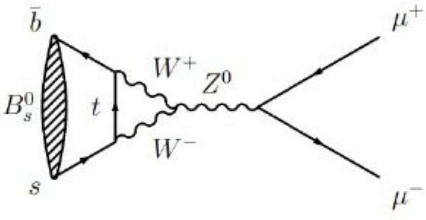
B to two muons: the emperor penguin

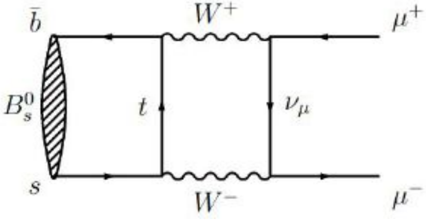
The ultimate experimental B decay for BSM searches

- **Highly suppressed in the SM**
  - $Br(B_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$
  - $Br(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$
- **Highly increasable elsewhere**
- **Experimentally accessible**
  - ATLAS, CMS, and LHCb in the game
- **Theoretically clean**
  - No hadrons in the final state

Beneke, Bobeth, Szafron
arXiv:1908.07011







B to two muons: the ATLAS measurement

JHEP 04 (2019) 098

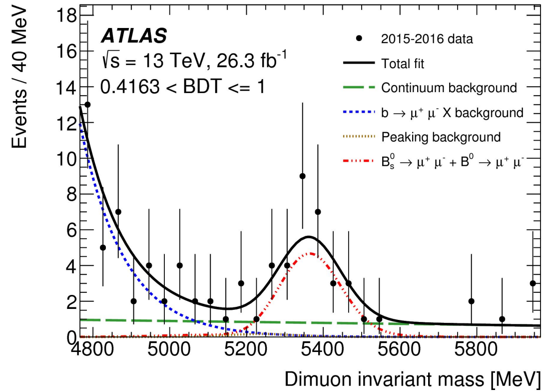
- **Partial Run2 analysis (L_{int} = 26.3 fb^{-1})**
- Measurement relative to $B^{\pm} \to J/\psi\, K^{\pm}$ with $B_s \to J/\psi\, \phi$ as control channel

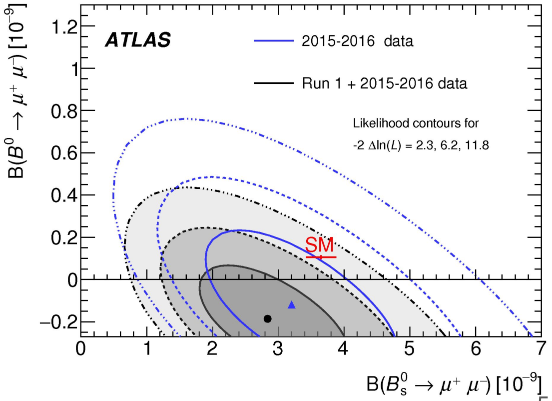
$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = N_{d(s)} \cdot \frac{\mathcal{B}(B^{\pm}\to J/\psi\, K^{\pm})\cdot\mathcal{B}(J/\psi\to\mu^+\mu^-)}{N_{J/\psi\, K^{\pm}}\cdot \epsilon_{\mu^+\mu^-}/\epsilon_{J/\psi\, K^{\pm}}} \cdot \frac{f_u}{f_{(s)}}$$

- Background reduction achieved with a BDT trained on sidebands data
- Event yields are obtained from fits to the mass spectra, with categories based on the BDT output
- Main backgrounds: partially reconstructed B hadrons decay, hadronic B_s decays where hadrons are misidentified as muons, combinatorial
- **Results** (Run1 + 2015 + 2016 data)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (2.8^{+0.8}_{-0.7}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10} \text{ at } 95\% \text{ CL}$$

- Compatible with the SM at 2.4σ
- Dominated by statistical uncertainties (still missing 2017 and 2018 data)

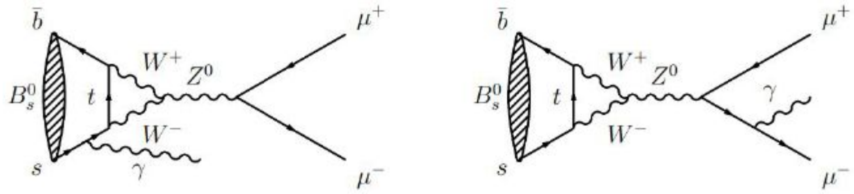


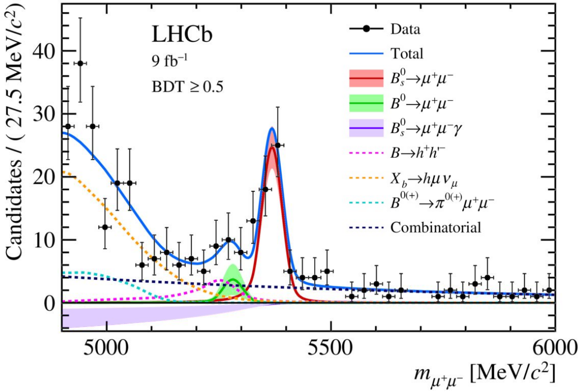


B to two muons: the LHCb measurement

PRL128(2022)041801
PRD105 (2022) 012010

- **Full Run1+Run2 analysis (L_{int} = 9 fb^{-1})**
- Initial State Radiation and Final State Radiation accounted for
  - ISR: hard distinguishable photon, lifts helicity suppression
  - FSR: soft photon, included experimentally as a radiative tail

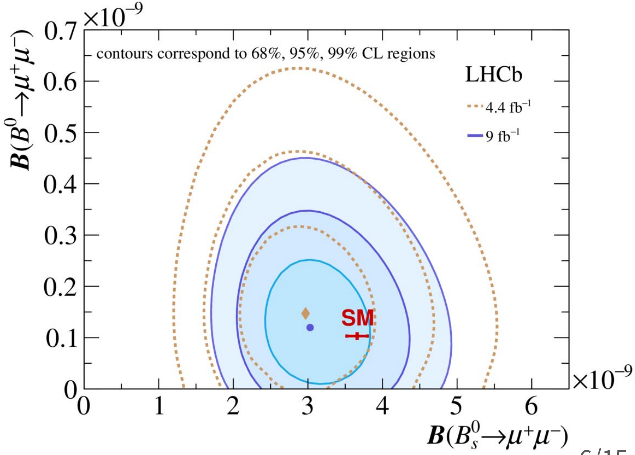




- **Results**
  - Branching ratios and limits at 95% CL

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46\,+0.15}_{-0.43\,-0.11}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)^{m(\mu\mu)>4.9\text{ GeV}} < 2.0 \times 10^{-9}$$

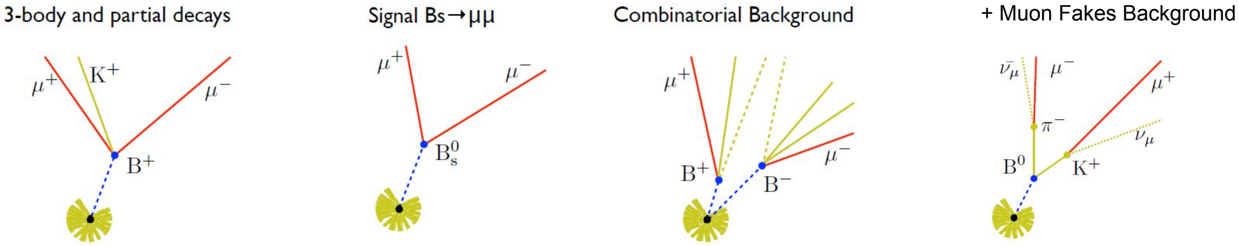
  - Effective lifetime $\tau_{\mu\mu} = 2.07 \pm 0.29 \pm 0.03$ ps
    - Consistent with only the heavy mass eigenstate decaying to two muons



B to two muons: the CMS measurement

CMS-PAS-BPH-21-006

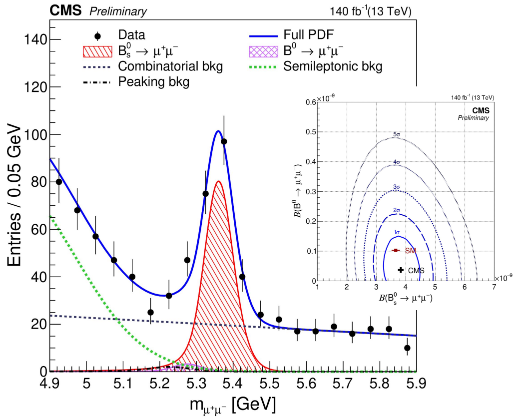
- **New full Run2 analysis (L_{int} = 140 fb^{-1})** (preliminary, not published)
- Dominant contributions

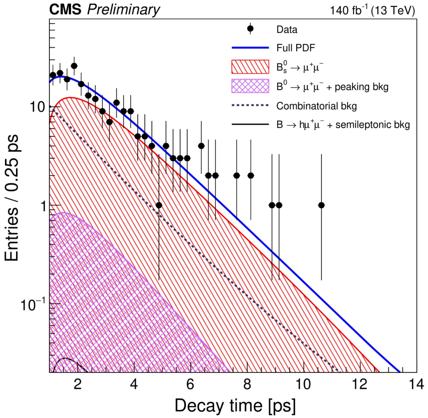


  - Hadrons misidentified as muons reduced with custom MVA ID
  - Dominant background suppressed with MVA
- **Results**

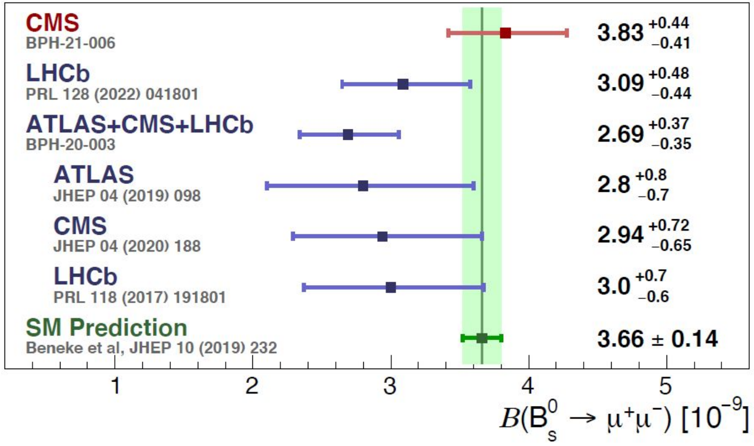
$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = [3.83^{+0.38}_{-0.36}\,(\text{stat})^{+0.19}_{-0.16}\,(\text{syst})^{+0.14}_{-0.13}\,(f_s/f_u)] \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = [0.37^{+0.75}_{-0.67}\,(\text{stat})^{+0.08}_{-0.09}\,(\text{syst})] \times 10^{-10}$$
$$\tau_{\mu\mu} = 1.83^{+0.23}_{-0.20}\,(\text{stat}) \pm 0.04\,(\text{syst})\,\text{ps}$$

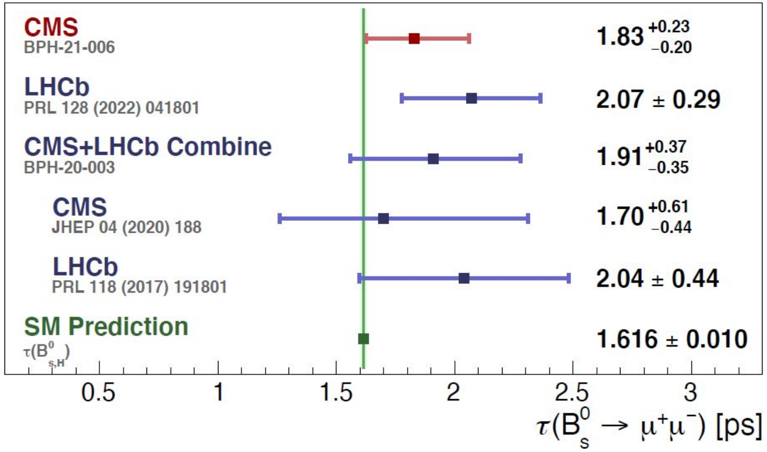
  - Consistent with the SM
  - Most precise single measurement to date, dominated by statistics

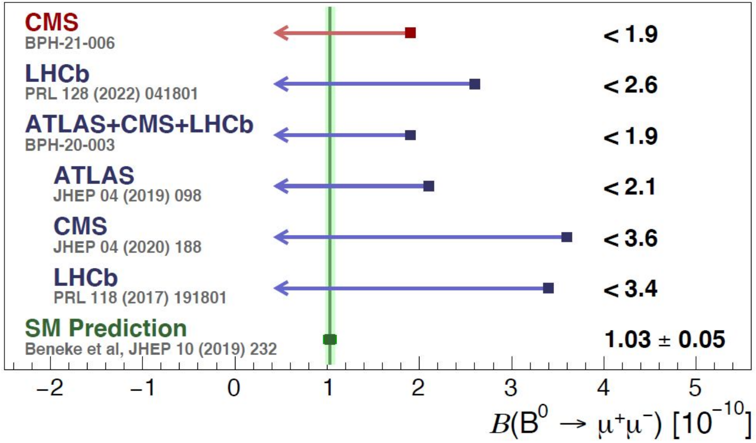




State-of-the-art with the new CMS result







- Two collaborations out of three have said their final piece for the LHC Run 1+2 legacy, waiting for ATLAS
- Good agreement with the SM for $B_s \to \mu^+\mu^-$, but a lot of work to do to observe $B^0 \to \mu^+\mu^-$

$$B_{(s)} \rightarrow ??$$

Beyond B → $\mu^+\mu^-$

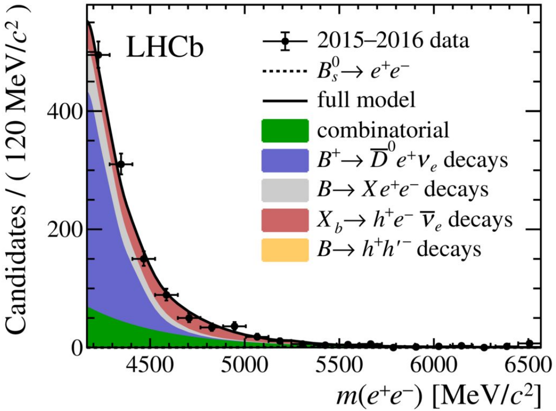
LHCb

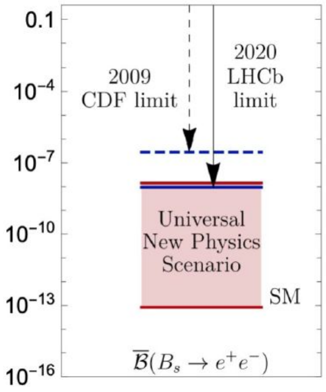
B to two electrons [PRL124(2020)211802]

- Even more suppressed in the SM (Br. ~ 10^{-15})
  - NP contributions up to ~ 10^{-8}
- Analysis performed with the Run1+2016 dataset
- **Limits** at 95% CL

$$\mathcal{B}(B_s^0 \to e^+e^-) < 11.2 \times 10^{-9}$$
$$\mathcal{B}(B^0 \to e^+e^-) < 3.0 \times 10^{-9}$$

Close to NP scenario region





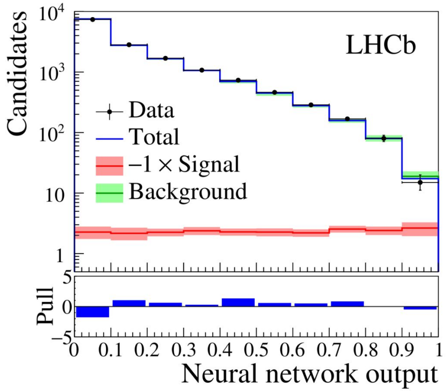
LHCb

B to two taus [PRL118(2017)251802]

- Less helicity suppression in the SM (Br. ~ 10^{-8})
- Analysis performed with the Run1 dataset
  - $\tau \to \pi\pi\pi\nu$ final state
- **Limits** at 95% CL

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3}$$

- **Mass not reconstructable → fit to DNN output**



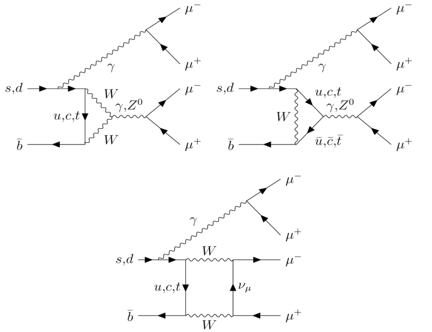
Beyond B → $\ell^+\ell^-$

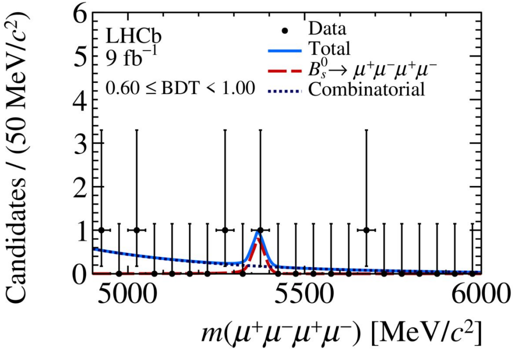
LHCb

B to four muons [JHEP03(2022)109]

- More suppressed (Br. ~ 10^{-10} - 10^{-12})
- Sensitive to different modes
- Experimentally clean (normalisation channel B → J/ψ(→μμ)ϕ(→μμ) with the same final state)
- **Limits** at 95% CL (Run1+2)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\mu^+\mu^-) < 8.6 \times 10^{-10}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 1.8 \times 10^{-10}$$



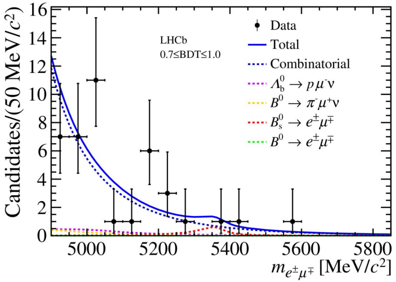


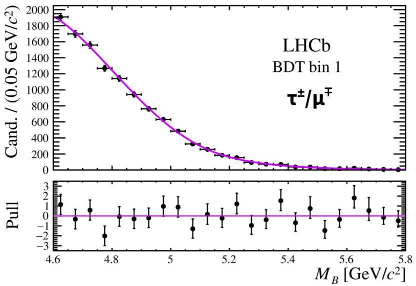
LHCb

B to e/μ, τ /μ [JHEP03(2018)078][PRL123(2019)211801]

- More than rare: forbidden in the SM
- LFV present in several models explaining LFU violation
- Analysis performed with the Run1 dataset
- **Limits** at 95% CL

$$\mathcal{B}(B_s^0 \to e^\pm\mu^\mp) < 6.3 \times 10^{-9}$$
$$\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 1.3 \times 10^{-9}$$
$$\mathcal{B}(B_s^0 \to \tau^\pm\mu^\mp) < 4.2 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to \tau^\pm\mu^\mp) < 1.4 \times 10^{-5}$$





Beyond B → leptons

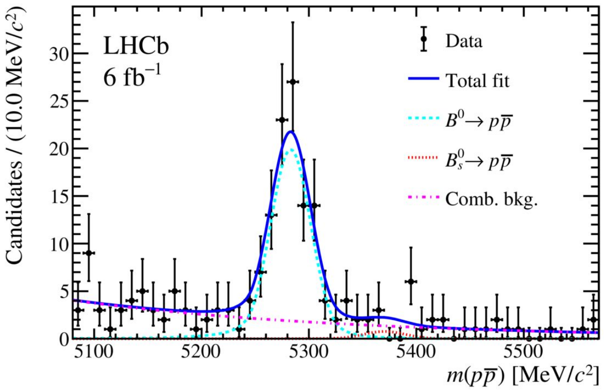
LHCb

B to pp

[arXiv:2206.06673]

- Suppressed w.r.t. multibody decays
- $B^0 \to K^+\pi^-$ as normalisation channel
- Analysis performed with the Run2 dataset
- **Results** (combined with Run1)

$$\mathcal{B}(B^0 \to p\bar{p}) = (1.27 \pm 0.13 \pm 0.05 \pm 0.03) \times 10^{-8}$$
$$\mathcal{B}(B^0_s \to p\bar{p}) < 5.1 \times 10^{-9} \text{ at } 95\% \text{ CL}$$



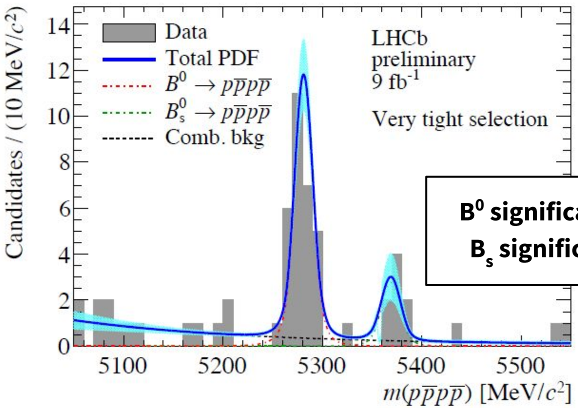
LHCb

B to pppp

[LHCb-PAPER-2022-032 in preparation]

- First observation of purely baryonic 4-body decay
- $B^0 \to J/\psi(pp)\ K^{*0}(K\pi)$ as normalisation channel
- Analysis performed with the Run1+2 dataset
- **Results** (combined with Run1)

$$\mathcal{B}(B^0 \to p\bar{p}p\bar{p}) = (2.2 \pm 0.3 \pm 0.1 \pm 0.1) \times 10^{-8}$$
$$\mathcal{B}(B^0_s \to p\bar{p}p\bar{p}) = (2.3 \pm 1.0 \pm 0.2 \pm 0.1) \times 10^{-8}$$



B^0 significance: >9σ
B_s significance: 4σ

Bonus: charm and strange decays to two muons

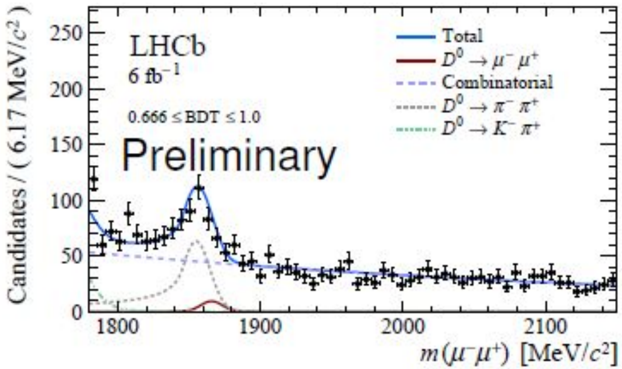
LHCb

D^0 to two muons [LHCb-PAPER-2022-029 in preparation]

- FCNC + helicity suppression (Br. ~ 10^{-11})
- Clean experimental signature and SM prediction
- Analysis performed with the Run1+2 dataset
- No signal observed, **limits** at 95% CL

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.3 \times 10^{-9}$$

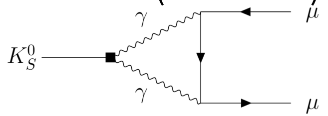
- Most stringent limit of FCNC in the charm sector



LHCb

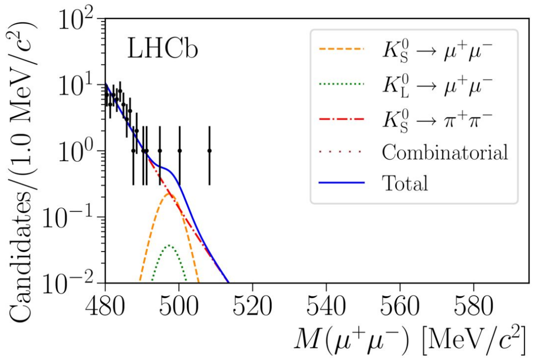
K^0_S to two muons [PRL125(2020)231801]

- Very rare in the SM (Br. ~ 10^{-12})



- Analysis performed with the Run2 dataset
- **Limits** (combined with Run1) at 95% CL

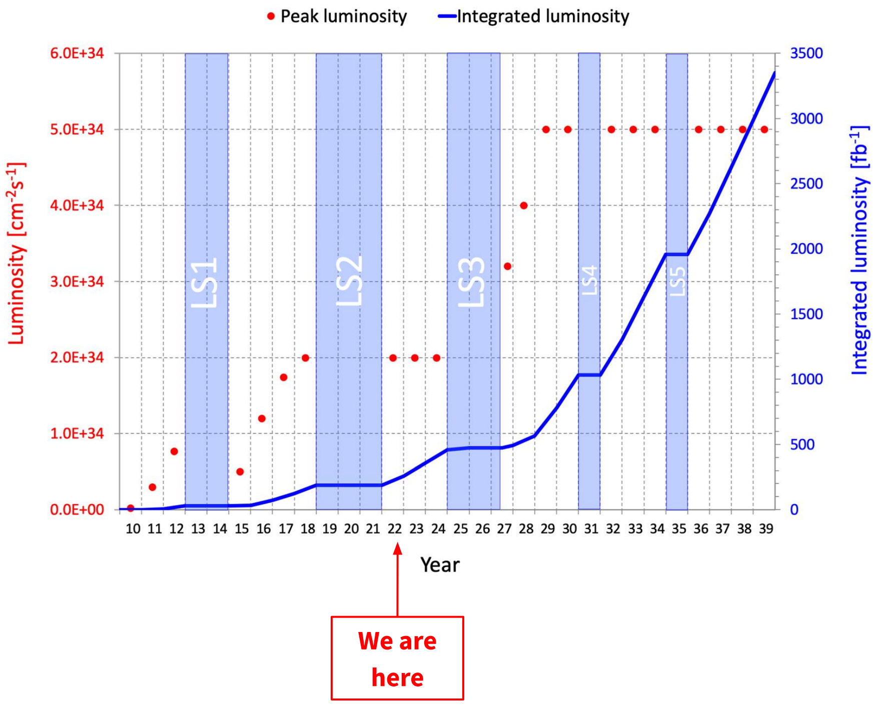
$$\mathcal{B}(K^0_S \to \mu^+\mu^-) < 2.4 \times 10^{-10}$$



Conclusions

Summary and outlook

- **Rare B decay constitutes a powerful tool to search for New Physics**
  - Theoretically clean (usually)
  - Highly sensitive to unknown particle contributions
- **$B_{(s)} \rightarrow \mu^+\mu^-$ stands as the flagship process**
  - ATLAS, CMS, and LHCb are all highly competitive and committed
- **As of today, all measurements are dominated by statistical uncertainties**
  - Good outlook for improvements with the next LHC runs
- **Run3 is starting now**
  - x2 higher luminosity for ATLAS/CMS
  - x5 higher luminosity for LHCb



Thanks for the attention

Backup

B to two muons: CMS analysis details 1

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

or $$\left\{= \mathcal{B}(B_s^0 \to J/\psi\phi) \times \frac{N_{B_s^0\to\mu^+\mu^-}}{N_{B_s^0\to J/\psi\phi}} \times \frac{\epsilon_{B_s^0\to J/\psi\phi}}{\epsilon_{B_s^0\to\mu^+\mu^-}}\right\}$$

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

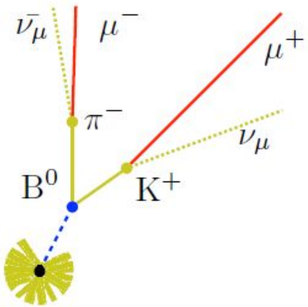
external B production fraction ratio

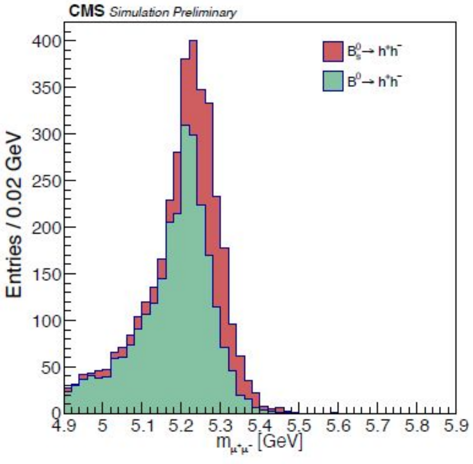
=1

Selection	$B_s^0 \to \mu^+\mu^-$	$B^+ \to J/\psi K^+$	$B_s^0 \to J/\psi\phi$
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
J/ψ candidate 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 MVA
  - Limited by trigger requirements
- **Normalization channel selection is optimized to match kinematics of signal**

B to two muons: CMS analysis details 2

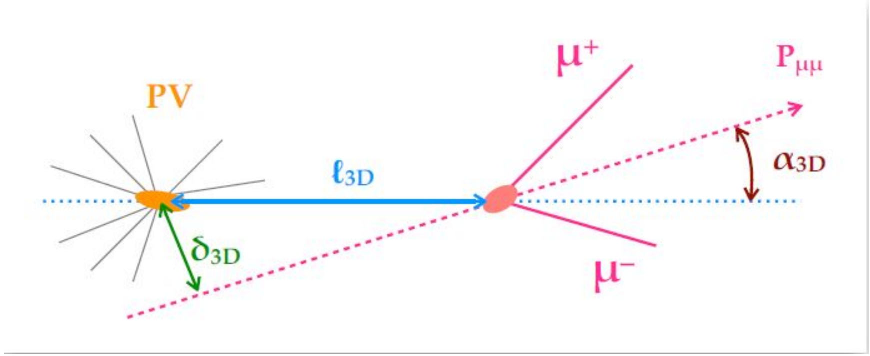


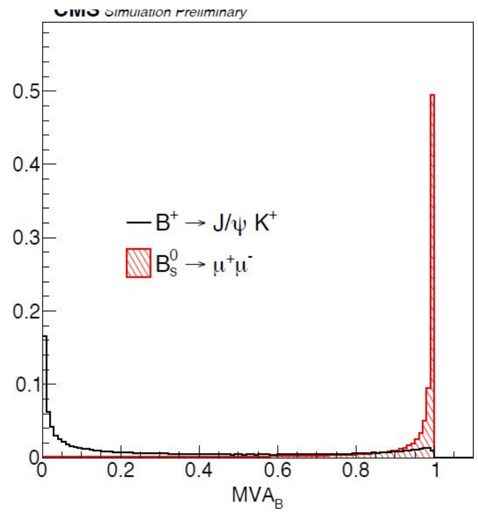


MUON FAKES

- **Double muon fakes from $B \to h^+h^-$ non-trivial background**
  - Looks like signal
  - Rate is comparable to $B^0 \to \mu\mu$
  - $B^0 \to K\pi$ and $B_s \to KK$ are dominant contribution
- **Primary source of fakes**
  - Pion and kaon decays in flight to muon and neutrino
  - Other contributions are negligible and easy to reject
- **Used MVA-based muon identification**
  - Detect minor imperfections in the muon candidate trajectory
  - Factor of 2-3 better rejection of fakes than the CMS standard muon selection
    - Kaon decays are easier to reject
- Fake rates are measured in $K_s \to \pi\pi$ and $\phi \to KK$ control samples
  - Simulated reasonably well: ~25% systematic per hadron

B to two muons: CMS analysis details 3





- **New multivariate analysis (MVA_B) used to suppress the dominant backgrounds**
  - Trained with signal MC and mass sideband data with the XGBoost package
- **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: $\ell_{3D}/\sigma(\ell_{3D})$
  - Isolation for B candidate and muons
  - Dimuon vertex quality
- **MVA mismodeling can be a major source of systematics**
  - Need a data control sample
  - $B^\pm \to J/\psi K^\pm$ is the best candidate
- **MVA is trained to rejected μμK events**
  - Extra track, wrong pointing angle etc
- **Need to use correct input to get signal-like response**
  - μμK: pointing angle, impact parameter
  - μμ: vertex probability, displacement, isolation (ignore kaon)

B to two muons: CMS analysis details 4

Branching fraction systematics

Effect	$BF(B_s \to \mu^+\mu^-)$	$BF(B^0 \to \mu^+\mu^-)$
Trigger efficiency	2–4%	
Pileup	1%	
Vertex quality	1%	
MVA_B correction	2–3%	
Tracking efficiency	2.3%	
$J/\psi K^+$ shape	1%	
Fit bias	2.2%	4.5%
f_s/f_u ratio	3.5%	-

Lifetime systematics

Effect	2016a	2016b	2017	2018
Efficiency modeling	0.01 ps			
Scanning over different gen lifetime sample	0.01 ps			
Decay time mis-modeling	0.10 ps	0.06 ps	0.02 ps	0.02 ps
Lifetime bias	0.04 ps	0.04 ps	0.05 ps	0.04 ps
Total	0.11 ps	0.07 ps	0.05 ps	0.04 ps

LHCb

B to protons: systematics

B to pp

Source of systematic uncertainties	$B^0 \to p\bar{p}$	$B_s^0 \to p\bar{p}$
f_s/f_d	-	3.1
L0 trigger efficiency	1.0	1.0
Selection efficiency relative to $B^0 \to K^+\pi^-$	2.0	2.0
Tracking efficiency	1.9	1.9
PID efficiency	2.4	2.4
Fit model	1.0	22.0
Total	3.9	22.5

Uncertainties in %

B to pppp

	$B^0 \to p\bar{p}p\bar{p}$	$B_s^0 \to p\bar{p}p\bar{p}$
Nominal $\mathcal{B}(B_{(s)}^0 \to p\bar{p}p\bar{p}) \times 10^{-8}$	2.21 ± 0.37	2.30 ± 0.96
Systematic source		
Efficiencies (MC stat)	0.02	0.03
Efficiencies (weights)	0.06	0.09
PID	0.03	0.03
Tracking	0.02	0.02
Fixed PDF parameters	0.02	0.02
Signal model	0.00	0.04
Background model	0.03	0.17
Quadratic sum	0.08	0.20
Normalisation $\mathcal{B}$	0.09	0.13

Uncertainties in absolute values

LHCb

B to four muons

- Full results, including resonances

Limits at 95% C.L.

$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\mu^+\mu^-\right) < 8.6 \times 10^{-10},$$
$$\mathcal{B}\left(B^0 \to \mu^+\mu^-\mu^+\mu^-\right) < 1.8 \times 10^{-10},$$
$$\mathcal{B}\left(B_s^0 \to a\left(\mu^+\mu^-\right) a\left(\mu^+\mu^-\right)\right) < 5.8 \times 10^{-10},$$
$$\mathcal{B}\left(B^0 \to a\left(\mu^+\mu^-\right) a\left(\mu^+\mu^-\right)\right) < 2.3 \times 10^{-10},$$
$$\mathcal{B}\left(B_s^0 \to J/\psi\left(\mu^+\mu^-\right) \mu^+\mu^-\right) < 2.6 \times 10^{-9},$$
$$\mathcal{B}\left(B^0 \to J/\psi\left(\mu^+\mu^-\right) \mu^+\mu^-\right) < 1.0 \times 10^{-9}.$$