Rare and semileptonic heavy flavour decays at LHCb

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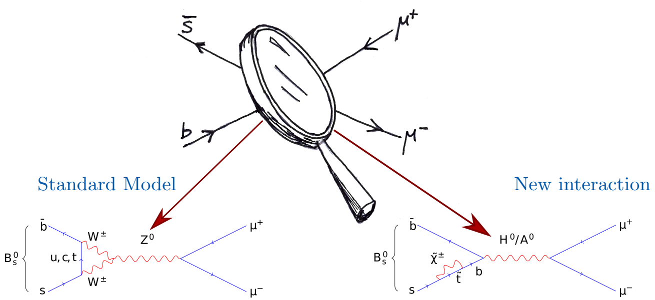
On behalf of the LHCb collaboration

56th Rencontres de Moriond 2022 QCD & High Energy Interactions
La Thuile - Valle d'Aosta, Italy

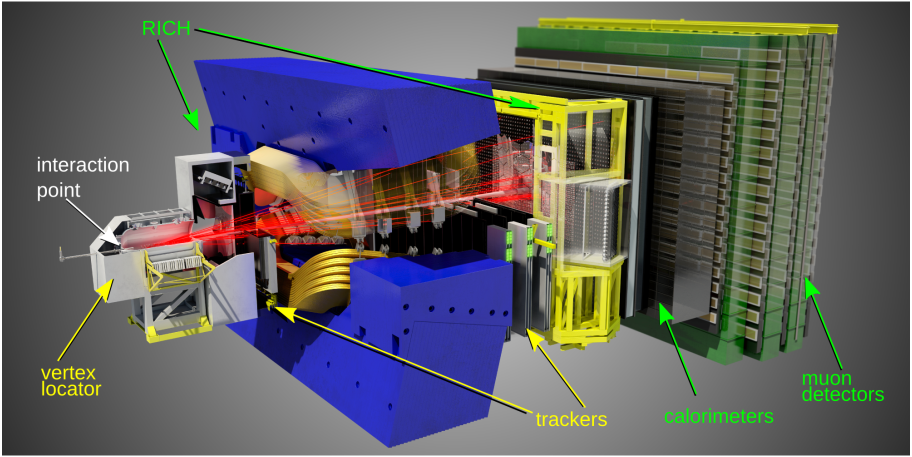
Why search indirectly for new interactions?



- Precise predictions in the SM
- Rare phenomena → New interactions can be major contribution
- New interactions can have different symmetries from the SM
- Charm and beauty probe complementary couplings

Example			
	Scalar interaction	Higgs-like boson	C_S, C_P
	Vector interaction	Z'	C_V, C_A

Over-constraining new interaction couplings is crucial to understand their origin



[Int. J. Mod. Phys. A 30 (2015) 1530022]

- pp collisions at $\sqrt{s} = 7, 8, 13$ TeV
- 3 (6) fb^{-1} in Run 1 (Run 2)

$B^0_{d,s} \to \mu^+\mu^-$ decays

Very rare decays

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

[Beneke, Bobeth, Szafron, JHEP10(2019) 232]

Similar predictions using the correlation with B mixing,

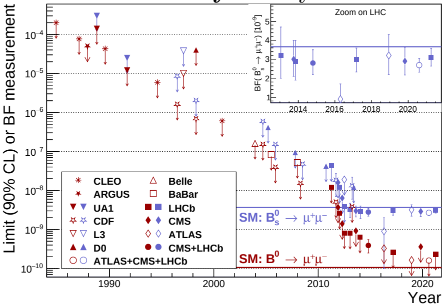
[Buras, Venturini -2109.11032]

- Summer 2020: 3 LHC experiments combined
- 2.1σ from SM in the 2D plane

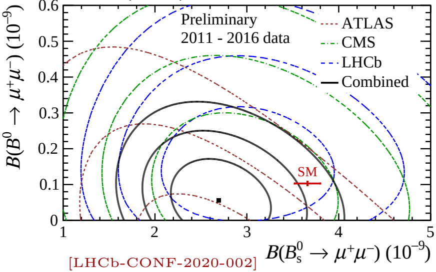
New LHCb analysis

- Full statistics: $9\,\text{fb}^{-1}$, two-fold increase in statistics w.r.t previous analysis
- Branching fractions and effective lifetime measurement
- Added $B^0_s \to \mu^+\mu^-\gamma$ search

History a 30 years search



ATLAS, CMS, LHCb - Summer 2020



[LHCb-CONF-2020-002]

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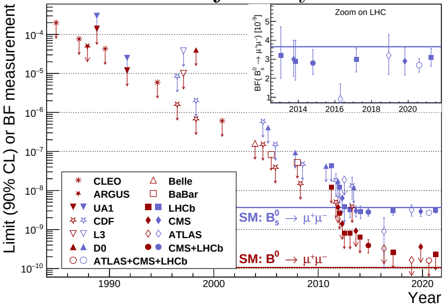

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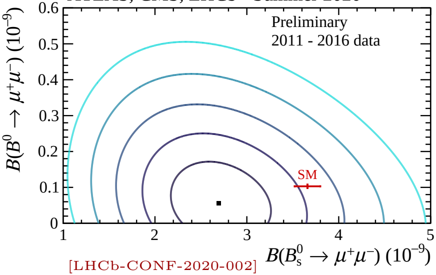
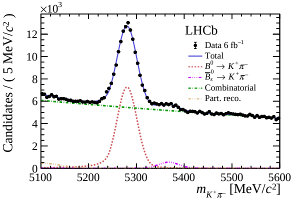


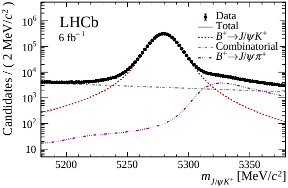
[LHCb-CONF-2020-002]

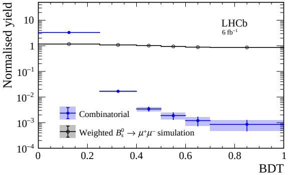
- Normalised to two channels: $B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$
- Multivariate operator against combinatorial background
- Tight PID calibrated on data against misID
- Significant improvement in hadronisation fraction $\frac{f_s}{f_d}(13\,\text{TeV}) = 0.2539 \pm 0.0079$ from combined measurement [LHCb-PAPER-2020-046 - PRD 104, 032005 (2021)]

[PRL128(2022)041801] [PRD105(2022)012010]

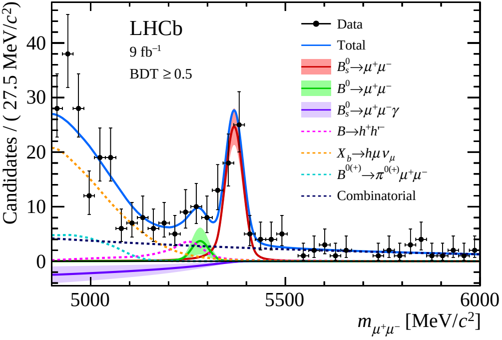
$$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-) = \underbrace{\frac{f_{\text{norm}}}{f_{\text{sig}}}}_{\text{Hadronisation fractions}} \overbrace{\frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}}}^{\text{Efficiencies}} \underbrace{\frac{N_{\text{sig}}}{N_{\text{norm}}}}_{\text{Yields}} \mathcal{B}(\text{norm}) = \underbrace{\alpha_{\text{sig}}}_{\text{Single event sensitivity}} \text{N}_{\text{sig}}$$







Results



- Simultaneous fit in 10 bins
  - 2 datasets (Run 1, 2) × 5 BDT bins
- External constraints on yield and shape of misidentified backgrounds
- Combinatorial background free
- Signal shapes calibrated and constrained
- All systematic uncertainties directly propagated

[PRL128(2022)041801] [PRD105(2022)012010]

$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9}$

$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(1.2\,^{+0.8}_{-0.7} \pm 0.1\right) \times 10^{-10} < 2.6 \times 10^{-10}$

$\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\,\mathrm{GeV}} = (-2.5 \pm 1.4 \pm 0.8) \times 10^{-9} < 2.0 \times 10^{-9}$

No significant signal for $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-\gamma$, upper limits at 95%

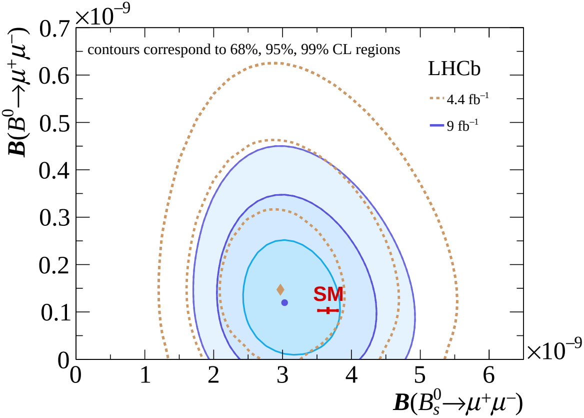
First world limit on $B^0_s \to \mu^+\mu^-\gamma$ decay

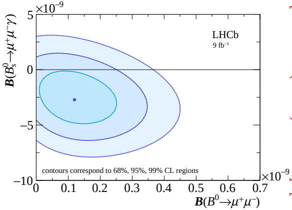
Measured effective lifetime $\tau_{\mathrm{eff}}(B^0_s \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03\,\mathrm{ps}$

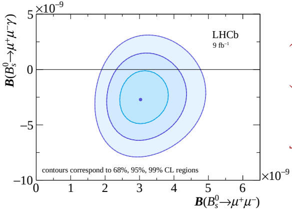
Consistent at 1.5σ and 2.2σ with the heavy and light B^0_s eigenstates lifetimes

$B^0_{d,s} \to \mu^+\mu^-$ analysis with full statistics

Closing the phase space







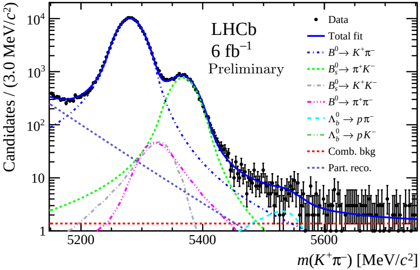
[PRL128(2022)041801] [PRD105(2022)012010]

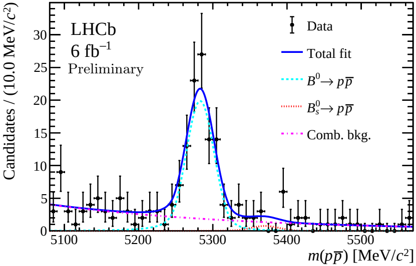
- Prior to LHC(b) orders of magnitude enhancements of the $B^0_{d,s} \to \mu^+\mu^-$ branching fractions were allowed
- Now closed to about 20% distance
- This tightens the phase-space for possible new physics that would cause (pseudo)-scalar or axial-vector $bs\mu\mu$ couplings

$B^0_{(s)} \to p\bar{p}$ decays

[LHCb-PAPER-2022-004]

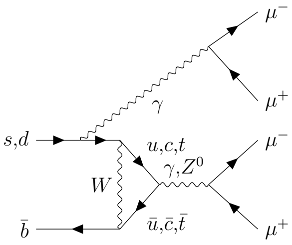
- Very rare baryonic modes
- Run 2 analysis, normalised to $B^0 \to K^+\pi^-$ decays
- $B^0 \to p\bar{p}$ (re)-observed with large significance and branching fraction
  $\mathcal{B}(B^0 \to p\bar{p}) = (1.27 \pm 0.15 \pm 0.05 \pm 0.04) \times 10^{-8}$
- Rarer $B^0_s \to p\bar{p}$ not observed, with upper limit
  $\mathcal{B}(B^0_s \to p\bar{p}) < 4.37(5.03) \times 10^{-9}$ at 90% (95%)
- Combined Run 1-2 branching fraction
  $\mathcal{B}(B^0 \to p\bar{p}) = (1.27 \pm 0.13 \pm 0.05 \pm 0.03) \times 10^{-8}$

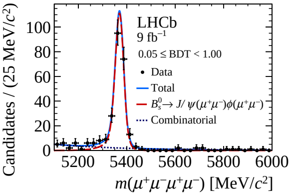




Search for B to four muons

- $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ very rare in the SM (non-resonant) $\mathcal{B}(B^0_s) \sim 10^{-10}$, $\mathcal{B}(B^0) \sim 10^{-12}$
- Many extension of the SM can give contributions orders of magnitude larger, such as MSSM [Demidov, Gorbunov] *
- In particular light axions that could explain the $g-2$ anomaly
  [Bauer, Neubert,Thamm - PRL119,031802(2017)]
  [Liu, Wagner, Wang - JHEP 03 (2019) 008]
  [Chala, Egede, Spannowsky - Eur.Phys.J.C 79 (2019) 5, 431]
- Use full Run1-2 statistics ($9\,\text{fb}^{-1}$), supersedes previous results
- Search for non-resonant $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$, axion mediated $B \to aa$ with $m_a = 1\,\text{GeV}$, and $B^0_{(s)} \to J/\psi\,(\mu^+\mu^-)\,\mu^+\mu^-$
- Normalisation to $B^0_s \to J/\psi(\mu^+\mu^-)\phi(\mu^+\mu^-)$, $\mathcal{B} = (1.74 \pm 0.14)10^{-8}$
- Search in bins of a BDT trained against combinatorial background
- Misidentified background found to be negligible





[LHCb-PAPER-2021-039 - hep-ex/2111.11339]

*Model sparked attention due to the HyperCP anomaly, later constrained by LHCb. See the LHCb evidence for $\Sigma^+ \to p\mu^+\mu^-$ decays [PRL120, 221803 (2018)]

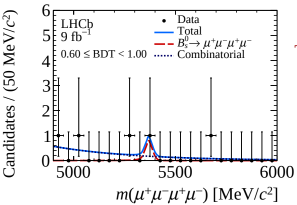
Search for B to four muons

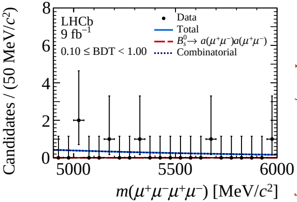
- No excess above background expectation found
- Limit with CLs method in GammaCombo

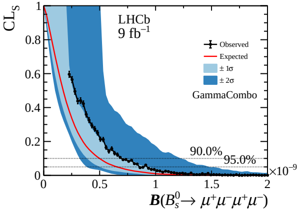
The limits at 95% confidence are

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

First search for $B \to aa$ with $m_a = 1\,\text{GeV}$
First limit on $B^0_{(s)} \to J/\psi\left(\mu^+\mu^-\right)\mu^+\mu^-$ decays
Factor 2 improvement on the non resonant channels.





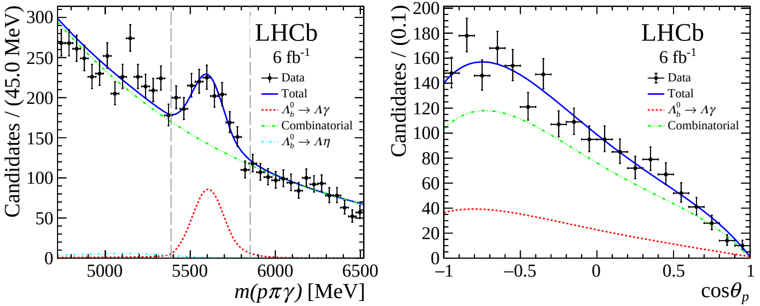


[LHCb-PAPER-2021-039 - hep-ex/2111.11339]

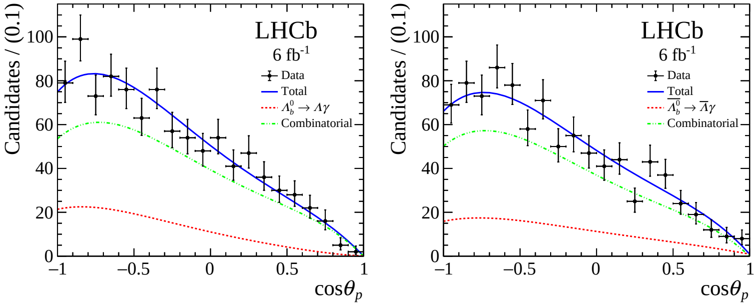
See also first search for $B^0 \to \phi(K^+K^-)\mu^+\mu^-$ [hep-ex/2201.10167] in backup.

[LHCb-PAPER-2021-030 - hep-ex/2111.10194]

- $b \to s\gamma$ photon polarisation in SM predominantly left-handed (deviations $\propto m_s^2/m_b^2$)
- Photon recoils against Λ that is in turn polarised
- Measure photon polarisation α_γ from proton angular distribution
- Sensitive to $C_7^{(\prime)}$ couplings
- Analysis based on $6\,\text{fb}^{-1}$ data triggered by the hadrons or photon
- BDT based selection against combinatorial background, small $\Lambda_b^0 \to \Lambda\eta$ residual background



Measurement of the photon polarization in $\Lambda_b^0 \to \Lambda\gamma$



[LHCb-PAPER-2021-030 - hep-ex/2111.10194]

- Signal described by $\frac{d\Gamma}{d\cos(\theta_p)} \propto 1 - \alpha_\Lambda \alpha_\gamma \cos(\theta_p)$ times acceptance function
- Use Λ decay parameter $\alpha_\Lambda = 0.754 \pm 0.004$ from BESIII [Nature Phys. 15 (2019) 631]
- Background by a 4^{th} order polynomial with coefficients determined from mass sidebands
- The photon polarization, with all systematic uncertainties
  $\alpha_\gamma = 0.82 \pm 0.23 \pm 0.13$
- Charge separated as measure of CP violation $\alpha_\gamma^- = 1.26 \pm 0.42 \pm 0.20$
  $\alpha_\gamma^+ = -0.55 \pm 0.32 \pm 0.16$

Measurement of the photon polarization in $\Lambda_b^0 \to \Lambda\gamma$

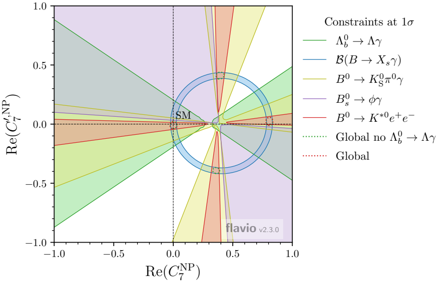
[LHCb-PAPER-2021-030 - hep-ex/2111.10194]

- Confidence intervals using Feldman-Cousins method imposing physical limits

$$\alpha_\gamma^- > 0.56(0.44) \text{ at } 90\% \ (95\%) \text{ CL}$$

$$\alpha_\gamma^+ = -0.56^{+0.36}_{-0.33}(stat.)^{+0.16}_{-0.09}(syst.),$$

$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}(stat.)^{+0.04}_{-0.13}(syst.)$$

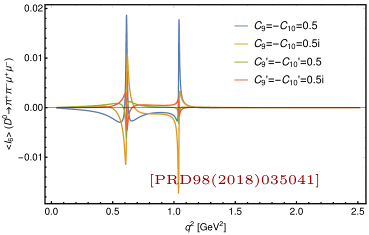


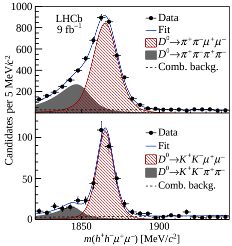
- This represents the first measurement of the photon polarisation in $b \to s\gamma$ decays
- Consistent with SM predictions and CP symmetry
- Constraints on Wilson coefficients with FLAVIO software
- Tightly constraining new C_7 currents: solving two fold ambiguity with C_7' currents

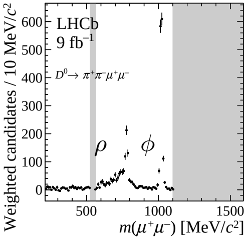
Angular analysis of $D^0 \to h^+h^-\mu^+\mu^-$ decays

[LHCb-PAPER-2021-035 - hep-ex/2111.03327]

- First full angular analysis of very rare $D^0 \to h^+h^-\mu^+\mu^-$ decays
- Full $9\,\text{fb}^{-1}$ statistics
- Regions dominated by resonances $D^0 \to h^+h^-R$ used as SM null tests
- Differential rate expressed in terms of 9 angular coefficients I_i
- Both flavour averages and CP asymmetries measured







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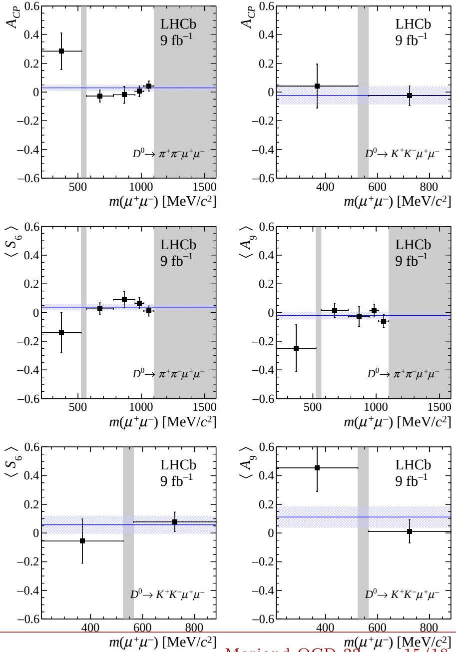


- First angular analysis of these very rare D decays
- The null test observables in agreement with SM at 0.3σ and 2.7σ for the $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ decays
- All measurements are consistent with SM predictions (where present) and CP symmetry

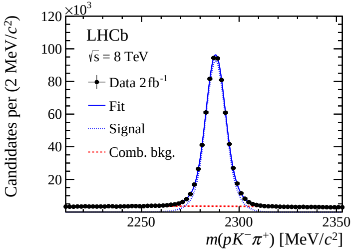
[LHCb-PAPER-2021-035 - hep-ex/2111.03327]

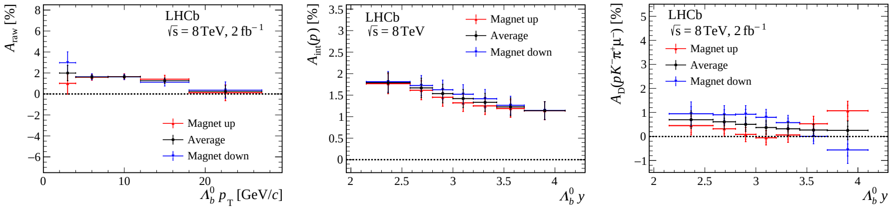
$\Lambda_b^0 - \overline{\Lambda}_b^0$ production asymmetry at $\sqrt{s} = 7$ and 8 TeV

- Production asymmetry fundamental for CP violation measurements
- Use semi-leptonic $\Lambda_b^0 \to \Lambda_c^+ \mu \bar{\nu}_\mu X$ decays
- Measure asymmetry in 3 fb^{-1} of pp data at $\sqrt{s} = 7$ and 8 TeV, in y and p_T bins

$$A_\mathrm{raw} = A_\mathrm{Prod} + A_\mathrm{det} + A_\mathrm{int} + A_\mathrm{PID} + A_\mathrm{trig}$$

- A_int from external measurements and $\Lambda \to p\pi$ control channel
- A_det canceled by swapping magnetic field
- A_PID and A_trig calibrated from control channels in data
- A_raw from fit to Λ_c^+ invariant mass fit

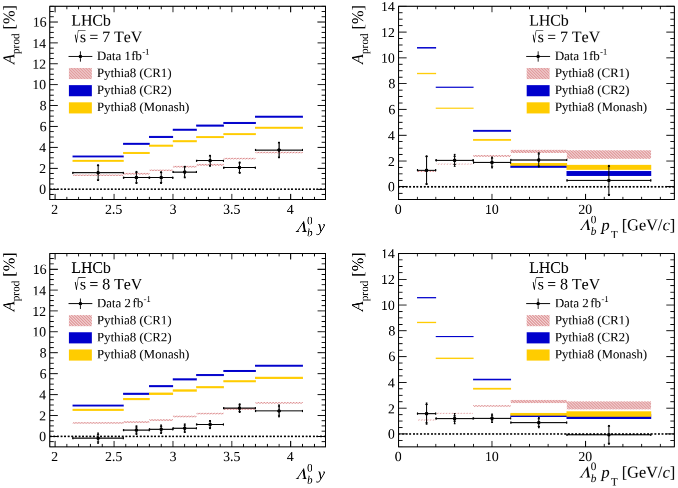




[LHCb-PAPER-2021-016- JHEP 10 (2021) 060]

$\Lambda_b^0 - \overline{\Lambda}_b^0$ production asymmetry at $\sqrt{s} = 7$ and $8\,\text{TeV}$

- Asymmetry is observed at 5.8σ significance, at $\sim 1\%$ level on average
- Evidence for a dependence on the rapidity
- Different Pythia tunings mostly overestimate the asymmetry, only one Colour Recombination model predicts correct low-p_{T} behaviours.
- Good comparison with Heavy-quark recombination model [PRD91(2015)054022]



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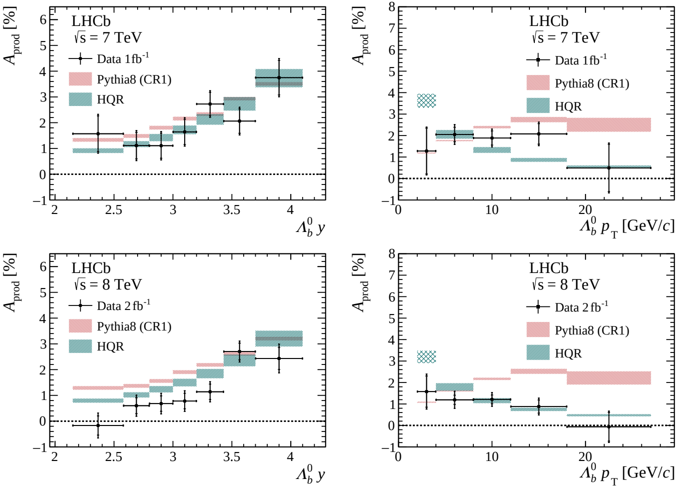


[LHCb-PAPER-2021-016- JHEP 10 (2021) 060]

Summary and conclusion

Legacy analyses from LHCb Run1-2 are being produced

- $B^0_{(s)} \to \mu^+\mu^-(\gamma)$ with world best single experiments results:
  - ⋆ first limit on $B^0_s \to \mu^+\mu^-\gamma$ decays
  - ⋆ Closing the phase space of (pseudo-)scalar or axial-vector new interactions
  - ⋆ looking forward to the full Run 1-2 analyses from ATLAS and CMS
- New $B^0_{(s)} \to p\bar{p}$ measurement
- Updated $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$search
  - ⋆ First search for $B \to aa$ with mass also around 1 GeV
  - ⋆ Strong constraints on all branching fractions
- Observation of photon polarisation in $\Lambda^0_b \to \Lambda\gamma$ decays
  - ⋆ Constraining new C_7 couplings
- Observation of Λ^0_b production asymmetry fundamental for future CP violation studies
- Measurements with charm decays tighten the space for models not constrained by the B

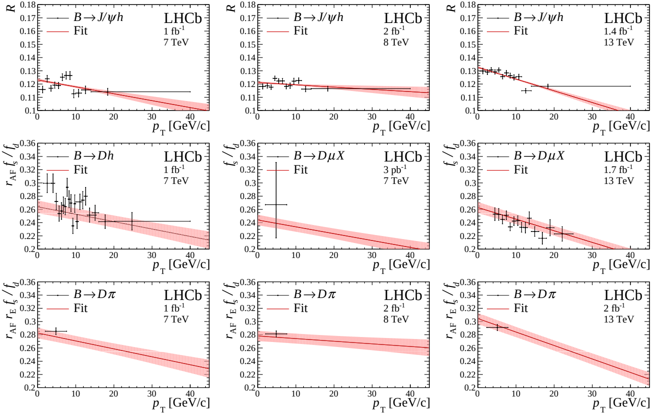
All of the very rare decays are statistically limited, and will be for some time
Looking forward to the collected data in Run 3 with the upgraded LHCb detector!

Backup

Combined measurement of hadronisation fraction

...and B_s^0 branching fractions

Breaking the recursive problem: combine information of different measurements
Measure production ratios from ratio of decays with known rate (semileptonic) or known rate ratios ($B \to Dh$), and cross-check dependencies with decays of high rate ($B \to J/\psi X$).
Recent LHCb combination $\frac{f_s}{f_d}(13\,\text{TeV}) = 0.2539 \pm 0.0079$



- ✓ Observed for the first time energy dependence
- ✓ Confirmed p_T dependence
- ✓ Precision improved by about a factor 2

[LHCb-PAPER-2020-046 - PRD 104, 032005 (2021)]

Combined measurement of hadronisation fraction

...and B_s^0 branching fractions

[LHCb-PAPER-2020-046 - PRD 104, 032005 (2021)]

More than 50 B_s^0 meson branching fractions updated, reducing significantly their uncertainties.

UPDATED

Decay mode	Updated branching fraction	Previous result		
$B_s^0 \to \phi\gamma$	$(3.75 \pm 0.18 \pm 0.12 \pm 0.12 \pm 0.24) \times 10^{-5}$	$(3.52 \pm 0.17 \pm 0.11 \pm 0.29 \pm 0.12) \times 10^{-5}$	[56]	⋆
$B_s^0 \to \mu^+\mu^-$	$(3.26 \pm 0.65^{+0.22}_{-0.11} \pm 0.10) \times 10^{-9}$	$(3.0 \pm 0.6^{+0.2}_{-0.1} \pm 0.2) \times 10^{-9}$	[57]	
$B_s^0 \to \overline{K}^{*0}\mu^+\mu^-$	$(3.09 \pm 1.07 \pm 0.21 \pm 0.10 \pm 0.22) \times 10^{-8}$	$(2.9 \pm 1.0 \pm 0.2 \pm 0.2 \pm 0.2) \times 10^{-8}$	[58]	
$B_s^0 \to \pi^+\pi^-\mu^+\mu^-$	$(8.66 \pm 1.50 \pm 0.47 \pm 0.28 \pm 0.60) \times 10^{-8}$	$(8.6 \pm 1.5 \pm 0.5 \pm 0.5 \pm 0.7) \times 10^{-8}$	[59]	⋆
$B_s^0 \to \phi\mu^+\mu^-$	$(7.54^{+0.43}_{-0.41} \pm 0.30 \pm 0.36) \times 10^{-7}$	$(7.97^{+0.45}_{-0.43} \pm 0.32 \pm 0.60) \times 10^{-7}$	[14]	⋆
$q^2 \in [1.0, 6.0]$	$(2.44^{+0.31}_{-0.30} \pm 0.07 \pm 0.12) \times 10^{-8}$	$(2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19) \times 10^{-8}$	[14]	⋆
$q^2 \in [15.0, 19.0]$	$(3.82^{+0.38}_{-0.36} \pm 0.12 \pm 0.18) \times 10^{-8}$	$(4.04^{+0.39}_{-0.38} \pm 0.13 \pm 0.30) \times 10^{-8}$	[14]	⋆
$q^2 \in [0.1, 2.0]$	$(5.54^{+0.69}_{-0.65} \pm 0.13 \pm 0.27) \times 10^{-8}$	$(5.85^{+0.73}_{-0.69} \pm 0.14 \pm 0.44) \times 10^{-8}$	[14]	⋆
$q^2 \in [2.0, 5.0]$	$(2.42^{+0.40}_{-0.38} \pm 0.06 \pm 0.12) \times 10^{-8}$	$(2.56^{+0.42}_{-0.39} \pm 0.06 \pm 0.19) \times 10^{-8}$	[14]	⋆
$q^2 \in [5.0, 8.0]$	$(3.03^{+0.42}_{-0.40} \pm 0.07 \pm 0.15) \times 10^{-8}$	$(3.21^{+0.44}_{-0.42} \pm 0.08 \pm 0.24) \times 10^{-8}$	[14]	⋆
$q^2 \in [11.0, 12.5]$	$(4.45^{+0.65}_{-0.62} \pm 0.14 \pm 0.21) \times 10^{-8}$	$(4.71^{+0.69}_{-0.65} \pm 0.15 \pm 0.36) \times 10^{-8}$	[14]	⋆
$q^2 \in [15.0, 17.0]$	$(4.28^{+0.54}_{-0.51} \pm 0.11 \pm 0.21) \times 10^{-8}$	$(4.52^{+0.57}_{-0.54} \pm 0.12 \pm 0.34) \times 10^{-8}$	[14]	⋆
$q^2 \in [17.0, 19.0]$	$(3.75^{+0.54}_{-0.51} \pm 0.13 \pm 0.18) \times 10^{-8}$	$(3.96^{+0.57}_{-0.54} \pm 0.14 \pm 0.30) \times 10^{-8}$	[14]	⋆

Decay mode	Updated branching fraction	Previous result		
$B_s^0 \to J/\psi K_S^0$	$(2.06 \pm 0.08 \pm 0.06 \pm 0.07 \pm 0.08) \times 10^{-5}$	$(1.93 \pm 0.08 \pm 0.05 \pm 0.11 \pm 0.07) \times 10^{-5}$	[60]	
$B_s^0 \to J/\psi K_S^0 K^\pm\pi^\mp$	$(5.01 \pm 0.35 \pm 0.33 \pm 0.16 \pm 0.44) \times 10^{-4}$	$(4.6 \pm 0.3 \pm 0.3 \pm 0.3 \pm 0.4) \times 10^{-4}$	[61]	⋆
$B_s^0 \to \psi(2S)\overline{K}^{*0}$	$(3.62 \pm 0.37 \pm 0.26 \pm 0.12 \pm 0.25) \times 10^{-5}$	$(3.35 \pm 0.34 \pm 0.24 \pm 0.19 \pm 0.22) \times 10^{-5}$	[62]	
$B_s^0 \to \psi(2S)K^+\pi^-$	$(3.43 \pm 0.23 \pm 0.14 \pm 0.11 \pm 0.24) \times 10^{-5}$	$(3.12 \pm 0.21 \pm 0.13 \pm 0.18 \pm 0.22) \times 10^{-5}$	[62]	
$B_s^0 \to J/\psi\eta$	$(4.04 \pm 0.35^{+0.32}_{-0.43} \pm 0.13 \pm 0.28) \times 10^{-4}$	$(3.79 \pm 0.31^{+0.20}_{-0.41} \pm 0.28 \pm 0.56) \times 10^{-4}$	[63]	⋆
$B_s^0 \to J/\psi\eta'$	$(3.67 \pm 0.32^{+0.14}_{-0.38} \pm 0.12 \pm 0.25) \times 10^{-4}$	$(3.42 \pm 0.30^{+0.14}_{-0.35} \pm 0.26 \pm 0.51) \times 10^{-4}$	[63]	⋆
$B_s^0 \to \psi(2S)\phi$	$(4.98 \pm 0.26 \pm 0.24 \pm 0.24) \times 10^{-4}$	$(5.33 \pm 0.28 \pm 0.26^{+1.37}_{-1.12}) \times 10^{-4}$	[12]	⋆
$B_s^0 \to \chi_{c1}\phi$	$(1.92 \pm 0.18 \pm 0.14 \pm 0.09) \times 10^{-5}$	$(1.98 \pm 0.19 \pm 0.15 \pm 0.20) \times 10^{-5}$	[64]	⋆
$B_s^0 \to J/\psi\pi^+\pi^-$	$(2.01 \pm 0.05 \pm 0.05 \pm 0.10) \times 10^{-4}$	$(2.16 \pm 0.05 \pm 0.06^{+0.51}_{-0.42}) \times 10^{-4}$	[11]	⋆
$B_s^0 \to J/\psi\phi\phi$	$(1.17 \pm 0.12^{+0.05}_{-0.09} \pm 0.06) \times 10^{-5}$	$(1.19 \pm 0.12^{+0.05}_{-0.09} \pm 0.10) \times 10^{-5}$	[15]	⋆
$B_s^0 \to J/\psi\overline{K}^{*0}$	$(4.12 \pm 0.19 \pm 0.13 \pm 0.20) \times 10^{-5}$	$(4.20 \pm 0.20 \pm 0.13 \pm 0.36) \times 10^{-5}$	[65]	⋆
$B_s^0 \to J/\psi p\bar{p}$	$(3.54 \pm 0.19 \pm 0.24 \pm 0.16) \times 10^{-6}$	$(3.58 \pm 0.19 \pm 0.24 \pm 0.30) \times 10^{-6}$	[66]	⋆
$B^0 \to J/\psi p\bar{p}$	$(3.94 \pm 0.35 \pm 0.26 \pm 0.13) \times 10^{-7}$	$(4.51 \pm 0.40 \pm 0.30 \pm 0.32) \times 10^{-7}$	[66]	⋆
$B_s^0 \to \psi(2S)\eta$	$(3.35 \pm 0.57 \pm 0.48 \pm 0.50) \times 10^{-4}$	$(3.15 \pm 0.53 \pm 0.45^{+0.61}_{-0.67}) \times 10^{-4}$	[67]	⋆
$B_s^0 \to \psi(2S)\eta'$	$(1.42 \pm 0.33 \pm 0.06 \pm 0.20) \times 10^{-4}$	$(1.32 \pm 0.31 \pm 0.05^{+0.26}_{-0.28}) \times 10^{-4}$	[68]	⋆
$B_s^0 \to J/\psi\pi^+\pi^-\pi^+\pi^-$	$(7.49 \pm 0.30 \pm 0.44 \pm 0.42) \times 10^{-5}$	$(7.62 \pm 0.36 \pm 0.64 \pm 0.42) \times 10^{-5}$	[69]	⋆
$B_s^0 \to \psi(2S)\pi^+\pi^-$	$(6.87 \pm 0.81 \pm 0.65 \pm 0.39) \times 10^{-5}$	$(7.3 \pm 0.9 \pm 0.6^{+1.9}_{-1.6}) \times 10^{-5}$	[67]	⋆

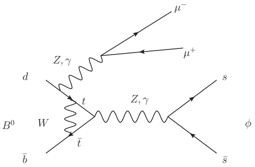
Decay mode	Updated branching fraction	Previous result		
$B_s^0 \to \pi^+\pi^-$	$(7.60 \pm 0.58 \pm 0.69 \pm 0.25 \pm 0.25) \times 10^{-7}$	$(6.91 \pm 0.54 \pm 0.63 \pm 0.40 \pm 0.19) \times 10^{-7}$	[70]	
$B_s^0 \to K^-\pi^+$	$(6.15 \pm 0.49 \pm 0.49 \pm 0.20 \pm 0.20) \times 10^{-6}$	$(5.4 \pm 0.4 \pm 0.4 \pm 0.4 \pm 0.2) \times 10^{-6}$	[71]	⋆
$B_s^0 \to K^+K^-$	$(2.63 \pm 0.08 \pm 0.16 \pm 0.09 \pm 0.09) \times 10^{-5}$	$(2.30 \pm 0.07 \pm 0.14 \pm 0.17 \pm 0.07) \times 10^{-5}$	[71]	⋆
$B_s^0 \to K_S^0 K_S^0$	$(8.28 \pm 1.60 \pm 0.90 \pm 0.26 \pm 0.81) \times 10^{-6}$	$(8.3 \pm 1.6 \pm 0.9 \pm 0.3 \pm 0.8) \times 10^{-6}$	[72]	
$B_s^0 \to K_S^0\pi^+\pi^-$	$(5.21 \pm 0.74 \pm 0.85 \pm 0.17 \pm 0.23) \times 10^{-6}$	$(4.7 \pm 0.7 \pm 0.8 \pm 0.3 \pm 0.2) \times 10^{-6}$	[73]	
$B_s^0 \to K_S^0 K^\pm\pi^\mp$	$(4.64 \pm 0.19 \pm 0.30 \pm 0.15 \pm 0.21) \times 10^{-5}$	$(4.22 \pm 0.18 \pm 0.28 \pm 0.25 \pm 0.17) \times 10^{-5}$	[73]	
$B_s^0 \to K^{*0}\overline{K}^{*0}$	$(2.70 \pm 0.44 \pm 0.43 \pm 0.09 \pm 0.19) \times 10^{-5}$	$(2.81 \pm 0.46 \pm 0.43 \pm 0.34 \pm 0.13) \times 10^{-5}$	[74]	⋆
$B_s^0 \to K^{*\pm}K^\mp$	$(1.23 \pm 0.18 \pm 0.13 \pm 0.04 \pm 0.07) \times 10^{-5}$	$(1.27 \pm 0.19 \pm 0.13 \pm 0.07 \pm 0.10) \times 10^{-5}$	[75]	
$B_s^0 \to K^{*-}\pi^+$	$(3.21 \pm 1.07 \pm 0.41 \pm 0.10 \pm 0.18) \times 10^{-6}$	$(3.3 \pm 1.1 \pm 0.4 \pm 0.2 \pm 0.3) \times 10^{-6}$	[75]	
$B_s^0 \to p\bar{p}K^\pm\pi^\mp$	$(1.41 \pm 0.23 \pm 0.12 \pm 0.05 \pm 0.11) \times 10^{-6}$	$(1.30 \pm 0.21 \pm 0.11 \pm 0.09 \pm 0.08) \times 10^{-6}$	[76]	
$B_s^0 \to p\Lambda K^\mp$	$(6.01 \pm 0.66 \pm 0.62 \pm 0.20 \pm 0.57) \times 10^{-6}$	$(5.46 \pm 0.61 \pm 0.57 \pm 0.32 \pm 0.50) \times 10^{-6}$	[77]	
$B_s^0 \to \phi\overline{K}^{*0}$	$(1.27 \pm 0.28 \pm 0.16 \pm 0.04 \pm 0.07) \times 10^{-6}$	$(1.10 \pm 0.24 \pm 0.13 \pm 0.08 \pm 0.06) \times 10^{-6}$	[78]	⋆
$B_s^0 \to \phi\phi$	$(2.02 \pm 0.05 \pm 0.08 \pm 0.07 \pm 0.11) \times 10^{-5}$	$(1.84 \pm 0.05 \pm 0.07 \pm 0.11 \pm 0.12) \times 10^{-5}$	[79]	
$B_s^0 \to \phi\pi^+\pi^-$	$(3.82 \pm 0.25 \pm 0.19 \pm 0.30) \times 10^{-6}$	$(3.48 \pm 0.23 \pm 0.17 \pm 0.35) \times 10^{-6}$	[80]	⋆
$B_s^0 \to \phi\phi\phi$	$(2.36 \pm 0.61 \pm 0.30 \pm 0.19) \times 10^{-6}$	$(2.15 \pm 0.54 \pm 0.28 \pm 0.21) \times 10^{-6}$	[81]	⋆

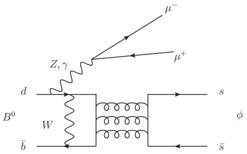
Decay mode	Updated branching fraction	Previous result		
$B_s^0 \to D_s^{*-}\mu^+\nu_\mu$	$(5.19 \pm 0.24 \pm 0.47 \pm 0.13 \pm 0.14) \times 10^{-2}$	$(5.38 \pm 0.25 \pm 0.48 \pm 0.20 \pm 0.15) \times 10^{-2}$	[53]	
$B_s^0 \to D_s^-\mu^+\nu_\mu$	$(2.40 \pm 0.12 \pm 0.15 \pm 0.06 \pm 0.10) \times 10^{-2}$	$(2.49 \pm 0.12 \pm 0.16 \pm 0.09 \pm 0.11) \times 10^{-2}$	[53]	
$B_s^0 \to D^+D_s^-$	$(3.01 \pm 0.32 \pm 0.10 \pm 0.08 \pm 0.34) \times 10^{-4}$	$(2.7 \pm 0.3 \pm 0.1 \pm 0.2 \pm 0.3) \times 10^{-4}$	[82]	
$B_s^0 \to D^+D^-$	$(2.47 \pm 0.46 \pm 0.23 \pm 0.08 \pm 0.22) \times 10^{-4}$	$(2.2 \pm 0.4 \pm 0.1 \pm 0.1 \pm 0.3) \times 10^{-4}$	[83]	
$B_s^0 \to D^0\overline{D}^0$	$(1.83 \pm 0.29 \pm 0.29 \pm 0.05 \pm 0.18) \times 10^{-4}$	$(1.9 \pm 0.3 \pm 0.2 \pm 0.2 \pm 0.3) \times 10^{-4}$	[83]	
$B_s^0 \to D_s^+D_s^-$	$(4.38 \pm 0.23 \pm 0.31 \pm 0.11 \pm 0.49) \times 10^{-3}$	$(4.0 \pm 0.2 \pm 0.2 \pm 0.2 \pm 0.4) \times 10^{-3}$	[83]	
$B_s^0 \to D^{*\pm}D^{*\mp}$	$(8.38 \pm 1.02 \pm 0.12 \pm 0.26 \pm 0.81) \times 10^{-5}$	$(8.41 \pm 1.02 \pm 0.12 \pm 0.39 \pm 0.79) \times 10^{-5}$	[84]	
$B_s^0 \to D_s^{+(*)}D_s^{-(*)}$	$(3.36 \pm 0.11 \pm 0.14 \pm 0.09 \pm 0.38) \times 10^{-2}$	$(3.05 \pm 0.10 \pm 0.13 \pm 0.14 \pm 0.34) \times 10^{-2}$	[85]	
$B_s^0 \to D_s^{*\pm}D_s^\mp$	$(1.49 \pm 0.06 \pm 0.07 \pm 0.04 \pm 0.17) \times 10^{-2}$	$(1.35 \pm 0.06 \pm 0.06 \pm 0.06 \pm 0.15) \times 10^{-2}$	[85]	
$B_s^0 \to D_s^{*+}D_s^{*-}$	$(1.39 \pm 0.09 \pm 0.10 \pm 0.04 \pm 0.16) \times 10^{-2}$	$(1.27 \pm 0.08 \pm 0.09 \pm 0.06 \pm 0.14) \times 10^{-2}$	[85]	
$B_s^0 \to \overline{D}^0 K_S^0$	$(4.69 \pm 0.51 \pm 0.28 \pm 0.15 \pm 0.64) \times 10^{-4}$	$(4.3 \pm 0.5 \pm 0.3 \pm 0.3 \pm 0.6) \times 10^{-4}$	[86]	
$B_s^0 \to \overline{D}^{*0} K_S^0$	$(3.05 \pm 1.13 \pm 0.40 \pm 0.10 \pm 0.41) \times 10^{-4}$	$(2.8 \pm 1.0 \pm 0.3 \pm 0.2 \pm 0.4) \times 10^{-4}$	[86]	
$B_s^0 \to \overline{D}^0\overline{K}^{*0}$	$(5.31 \pm 1.22 \pm 0.54 \pm 0.17 \pm 0.35) \times 10^{-4}$	$(4.72 \pm 1.07 \pm 0.48 \pm 0.37 \pm 0.74) \times 10^{-4}$	[87]	⋆
$B_s^0 \to \overline{D}^0 K^-\pi^+$	$(1.11 \pm 0.05 \pm 0.07 \pm 0.04 \pm 0.06) \times 10^{-3}$	$(1.00 \pm 0.04 \pm 0.06 \pm 0.08 \pm 0.10) \times 10^{-3}$	[88]	⋆
$B_s^0 \to \overline{D}^0\phi$	$(3.25 \pm 0.38 \pm 0.19 \pm 0.11 \pm 0.18) \times 10^{-5}$	$(3.0 \pm 0.3 \pm 0.2 \pm 0.2 \pm 0.2) \times 10^{-5}$	[89]	⋆
$B_s^0 \to \overline{D}^{*0}\phi$	$(4.01 \pm 0.48 \pm 0.27 \pm 0.13 \pm 0.23) \times 10^{-5}$	$(3.7 \pm 0.5 \pm 0.2 \pm 0.2 \pm 0.2) \times 10^{-5}$	[89]	⋆
$B_s^0 \to \overline{D}^0 K^+K^-$	$(6.13 \pm 0.59 \pm 0.28 \pm 0.20 \pm 0.56) \times 10^{-5}$	$(5.7 \pm 0.5 \pm 0.2 \pm 0.3 \pm 0.5) \times 10^{-5}$	[90]	⋆
$B_s^0 \to D_s^\mp K^\pm$	$(2.41 \pm 0.05 \pm 0.06 \pm 0.14) \times 10^{-4}$	$(2.29 \pm 0.05 \pm 0.06 \pm 0.17) \times 10^{-4}$	[91]	⋆
$B_s^0 \to D_s^-\pi^+\pi^-\pi^+$	$(6.43 \pm 1.18 \pm 0.64 \pm 0.38) \times 10^{-3}$	$(6.01 \pm 1.11 \pm 0.60 \pm 0.48) \times 10^{-3}$	[92]	⋆
$B_s^0 \to D_s^- K^+\pi^-\pi^+$	$(3.34 \pm 0.32 \pm 0.19 \pm 0.73) \times 10^{-4}$	$(3.13 \pm 0.30 \pm 0.18 \pm 0.76) \times 10^{-4}$	[93]	⋆
$B_s^0 \to D_{s1}(2536)^-\pi^+$	$(2.57 \pm 0.64 \pm 0.26 \pm 0.56) \times 10^{-5}$	$(2.41 \pm 0.60 \pm 0.24 \pm 0.58) \times 10^{-5}$	[93]	⋆

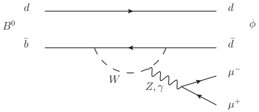
Search for $B^0 \to \phi\mu^+\mu^-$ decays

[LHCb-PAPER-2021-042]

- Rare decay in the SM (penguin CKM / OZI suppressed) $b \to d\mu^+\mu^-$ FCNC
- Short distance $\mathcal{B} \sim 10^{-12}$
- Including $\omega - \phi$ mixing could raise at $10^{-11} - 10^{-10}$ level
- New physics contributions such as Z' could enhance this



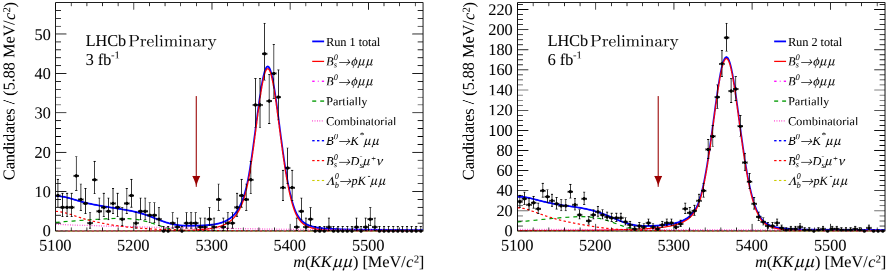




Search for $B^0 \to \phi\mu^+\mu^-$ decays

[LHCb-PAPER-2021-042]

- Normalised to $B_s^0 \to \phi\mu^+\mu^-$ decays
- $B_s^0 \to J/\psi\phi$ decays as control channel
- Main background: $B^0 \to K^*\mu^+\mu^-$, $\Lambda_b^0 \to pK^-\mu^+\mu^-$



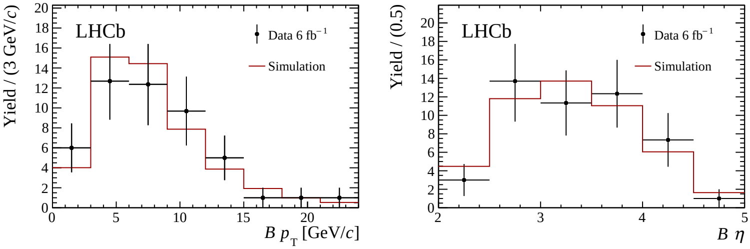
No excess over background expectation, upper limit

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)} < 4.4 \times 10^{-3} \text{ at } 90\% \text{ CL} .$$

$$\mathcal{B}(B^0 \to \phi\mu^+\mu^-) < 2.3(3.2) \times 10^{-9} \text{ at } 90\% \text{ CL} .$$

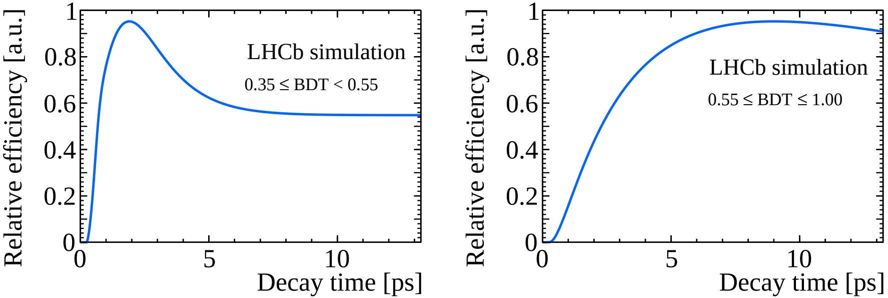
excluding ϕ and charmonia dimuon regions (extrapolating to full q^2)

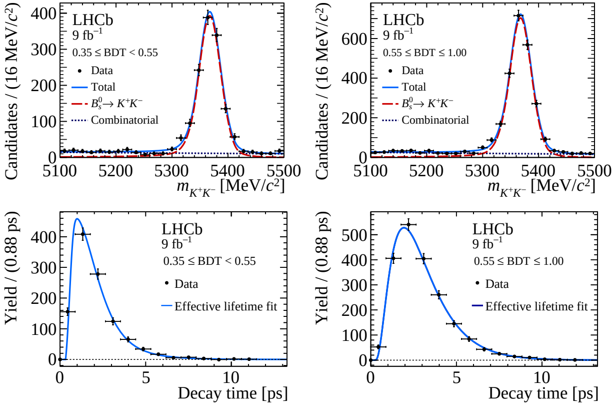
Distributions of $B_s^0 \to \mu^+\mu^-$ decays kinematics in data



[LHCb-PAPER-2021-007] [LHCb-PAPER-2021-008]

Decay time acceptance for $B_s^0 \to \mu^+\mu^-$ decays



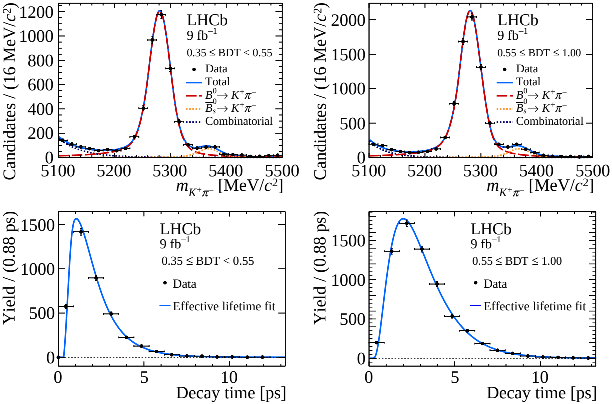


Measurement (stat only)

$$\tau_{B_s^0 \to K^+K^-} = 1.435 \pm 0.026\,\text{ps}$$

In agreement with published

$$\tau_{B_s^0 \to K^+K^-} = 1.407 \pm 0.016\,\text{ps}$$



Measurement (stat only)

$$\tau_{B^0 \to K^+\pi^-} = 1.510 \pm 0.015\,\text{ps}$$

In agreement with published

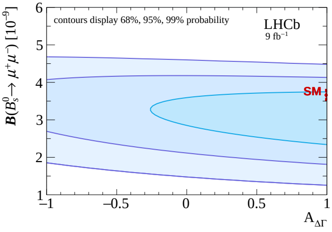
$$\tau_{B^0 \to K^+\pi^-} = 1.524 \pm 0.011\,\text{ps}$$

[LHCb-PAPER-2021-007] [LHCb-PAPER-2021-008]

The branching fraction measurement is affected by the effective lifetime, through the efficiency *

→ Hence there is a correlation between the two measurements

Both are thus sensitive to $A_{\Delta\Gamma}$

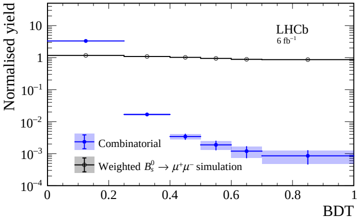


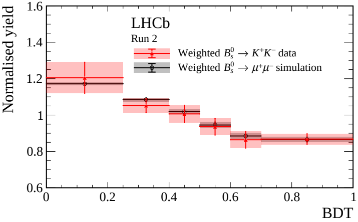
*See e.g. [F.D. , Guadagnoli, Phys.Lett.B 784 (2018) 96-100]

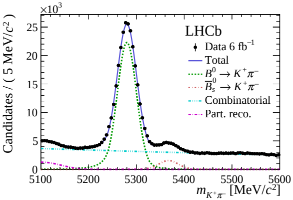
Calibration

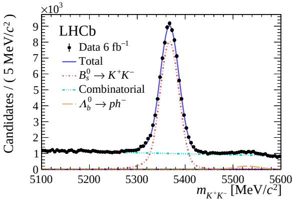
Search in mass distribution in bins of multivariate discriminant (BDT)

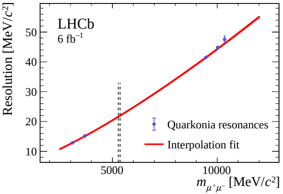
- BDT shape calibrated from simulation and $B \to h^+h^-$ in data
- Mass shape calibrated from quarkonia and $B \to h^+h^-$ in data











[LHCb-PAPER-2021-007] [LHCb-PAPER-2021-008]

$B^0_{d,s} \to \mu^+\mu^-$ observables

1. Branching fraction

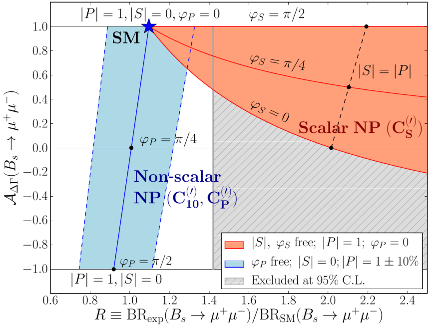
$$\mathcal{B}^{t=0}(B^0_s \to \mu^+\mu^-) = \frac{G_F^4 M_W^4}{\pi^2} \tau_{B^0_s} f^2_{B_s} m^3_{B_s} \sqrt{1-\frac{4m^2_\mu}{m^2_{B_s}}} |V_{tb}V^*_{ts}|^2 \left(\left|2\frac{m_\mu}{m_{B_s}}(C_{10}-C'_{10}) + C_P - C'_P\right|^2 + |C_S - C'_S|^2 \right)$$

2. Ratio of branching fractions

$$\mathcal{R} = \frac{\mathcal{B}(B^0 \to \mu^+\mu^-)}{\mathcal{B}(B^0_s \to \mu^+\mu^-)} = \frac{\tau_{B_d}}{\tau_{B_s}} \left(\frac{f_{B_d}}{f_{B_s}}\right)^2 \left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{m_{B_d}\sqrt{1-\frac{4m^2_\mu}{m^2_{B_d}}}}{m_{B_s}\sqrt{1-\frac{4m^2_\mu}{m^2_{B_s}}}}$$

3. Effective lifetime
   B^0_s mesons oscillate and mix into their mass eigenstates, the effective lifetime depends on which eigenstate decays to $\mu^+\mu^-$

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



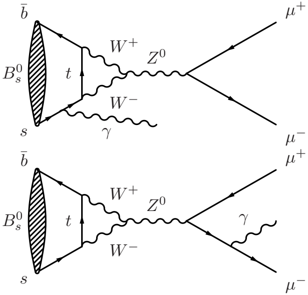
[De Bruyn et al. PRL109, 041801 (2012)]

$B_s^0 \to \mu^+\mu^-\gamma$ as an additional observable

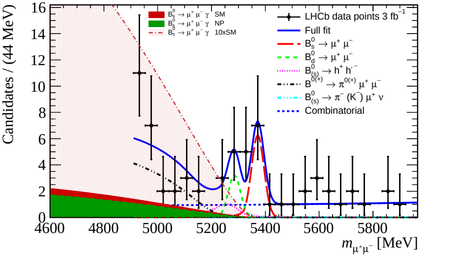
The radiative $B_s^0 \to \mu^+\mu^-\gamma$ decay is very interesting:

- Not helicity suppressed - as rare as $B_s^0 \to \mu^+\mu^-$
- Sensitive to vector couplings (C_9) (not just scalar or axial-vector)
- Can be split in initial (ISR) and final state radiation (FSR - bremsstrahlung)

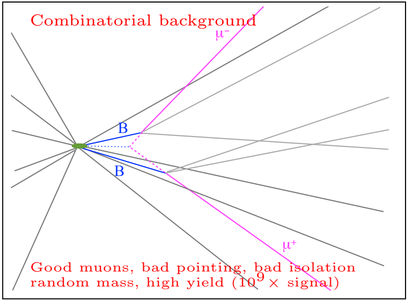
New method: measure the $B_s^0 \to \mu^+\mu^-\gamma$ rate without photon reconstruction from the left sideband of the $B_s^0 \to \mu^+\mu^-$ analysis.

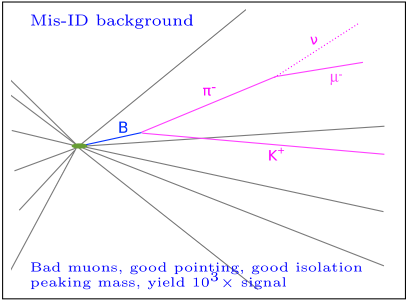


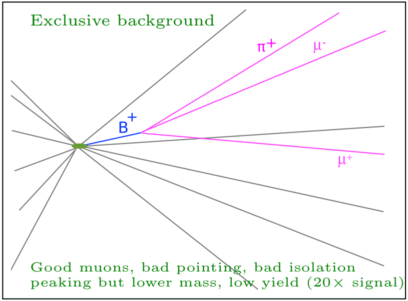
[F.D., Guadagnoli, Reboud - Phys.Lett.B 768 (2017)]

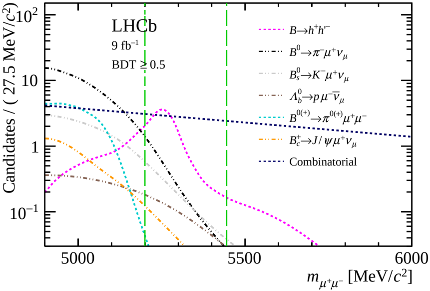


Backgrounds









[PRL128(2022)041801] [PRD105(2022)012010]

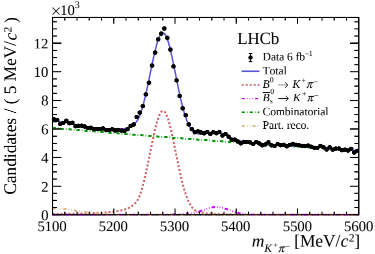
Normalisation

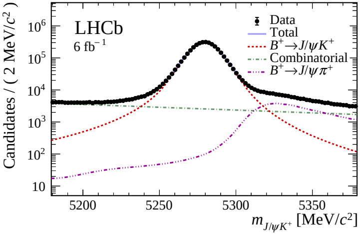
Convert yields to branching fractions by normalising to channels of known rate

$$\mathcal{B}(B^0_{d,s} \to \mu^+\mu^-) = \underbrace{\frac{f_{\rm norm}}{f_{\rm sig}}}_{\text{Hadronisation fractions}} \overbrace{\frac{\varepsilon_{\rm norm}}{\varepsilon_{\rm sig}}}^{\text{Efficiencies}} \underbrace{\frac{N_{\rm sig}}{N_{\rm norm}}}_{\text{Yields}} \mathcal{B}(\text{norm}) = \underbrace{\alpha_{\rm sig}}_{\text{Single event sensitivity}} \mathrm{N}_{\rm sig}$$

Use two channels

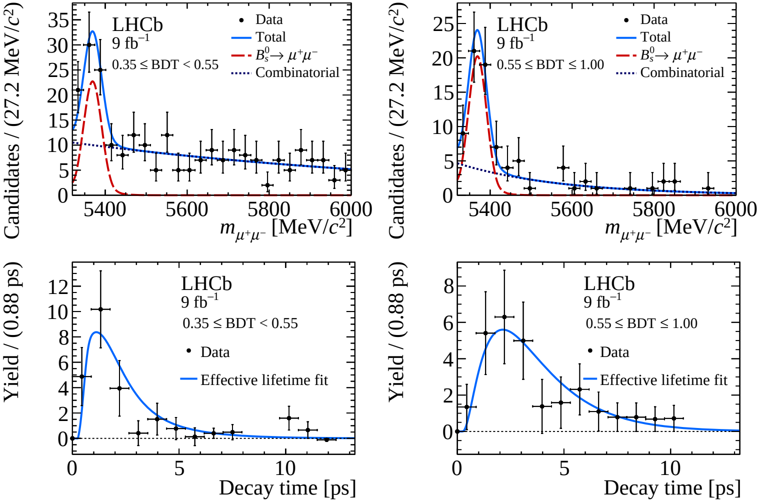
- $B^+ \to J/\psi K^+$- same trigger & PID as signal
- $B^0 \to K^+\pi^-$- same topology of signal





[PRL128(2022)041801] [PRD105(2022)012010]

Measurement of the effective lifetime



[PRL128(2022)041801] [PRD105(2022)012010]

$$\tau_{\rm eff}(B_s^0 \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03\,\text{ps}$$

Consistent at 1.5σ and 2.2σ with the heavy and light B_s^0 eigenstates lifetimes ($\tau_L = 1.423 \pm 0.005\,\text{ps}$ and $\tau_H = 1.620 \pm 0.007\,\text{ps}$)

The $B^0_{d,s} \to \mu^+\mu^-$ decays

Extremely rare decays

- Flavour changing neutral currents
- Helicity suppressed

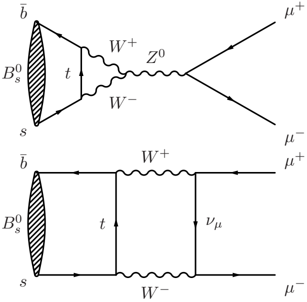
Most recent Standard Model predictions

$$B(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

[Beneke, Bobeth, Szafron, JHEP10(2019) 232]

- Impressively precise predictions
- Any significant deviations from these values is sign of new interactions beyond the SM
- Dominated by parametric uncertainties



Using the correlation of $\Delta F = 1$ rare decays with $\Delta F = 2$ B mixing, using experimental ΔM values can also be predicted to be:

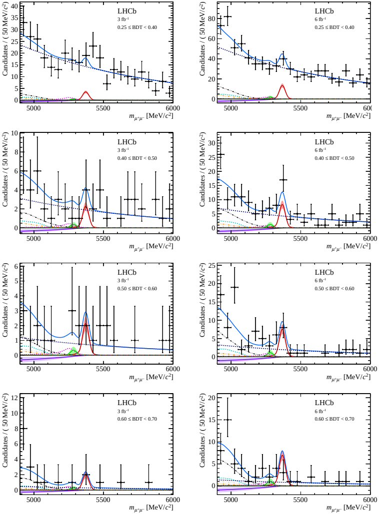
$$B(B^0_s \to \mu^+\mu^-) = (3.62^{+0.15}_{-0.10}) \times 10^{-9}$$
$$B(B^0 \to \mu^+\mu^-) = (0.99^{+0.05}_{-0.03}) \times 10^{-10}$$

[Buras, Venturini -2109.11032]

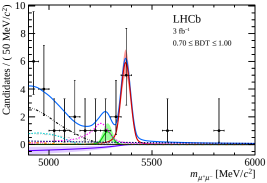
$B^0_{d,s} \to \mu^+\mu^-$ analysis with full statistics

Final invariant mass fit

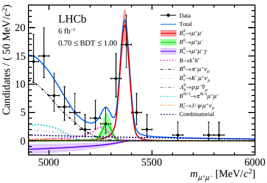
Run 1 Run 2



Run 1



Run 2



- Simultaneous fit in 10 bins
  2 datasets (Run 1, 2) × 5 BDT bins
- External constraints on yield and shape of misidentified backgrounds
- Combinatorial background free
- Signal shapes calibrated and constrained
- All systematic uncertainties directly propagated

[PRL128(2022)041801] [PRD105(2022)012010]