

# Experimental status of $b \rightarrow s \{\mu^+ \mu^-, e^+ e^-, \gamma\}$ at the LHC

## 21st Conference on Flavor Physics and $CP$ Violation (FPCP 2023)

### May 29, 2023

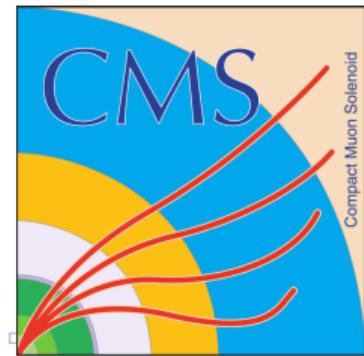


Riley Henderson

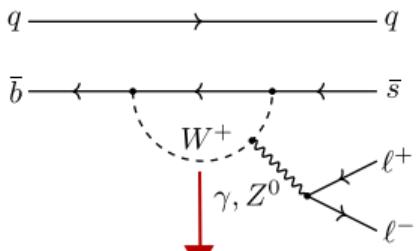
on behalf of the LHCb, ATLAS, and CMS collaborations



MONASH University



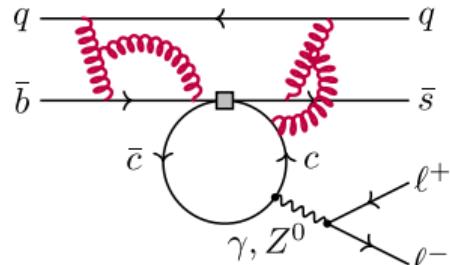
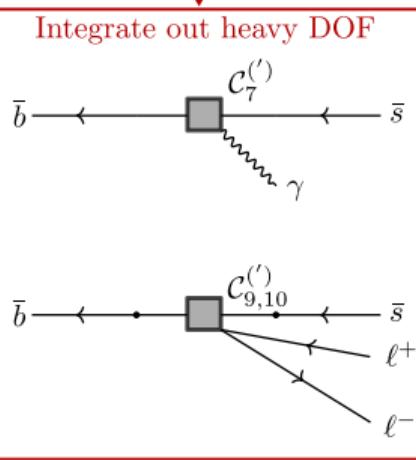
# Theory of $b \rightarrow s$ decays



- $b \rightarrow s$  is a FCNC quark transition — loop suppressed in the Standard Model.
- Described by Weak Effective Hamiltonian:

$$\mathcal{H}_{\text{eff}} = \frac{-4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i C_i \mathcal{O}_i$$

- Sensitive to New Physics in electroweak penguin and (pseudo)scalar operators.

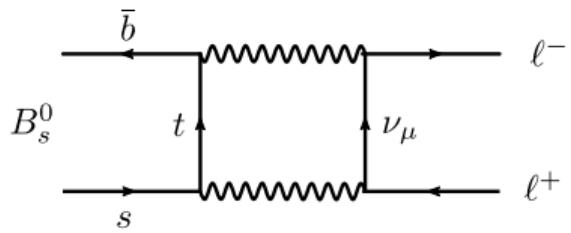


## QCD complications

- Quarks are bound in hadrons  $\rightarrow$  local form factors.
- Insertion of  $q\bar{q}$  loop  $\rightarrow$  non-local form factors + non-factorisable soft gluon corrections.

	Wilson coeff.	Operator	
$\gamma$ -penguin	$C_7^{(')}$	$\sim (\bar{s}\sigma_{\mu\nu} P_{R(L)} \bar{b}) F^{\mu\nu}$	See talks by N. Gubernari and Y. Monceaux for more on QCD in $b \rightarrow s$ decays
EW-penguins (V)	$C_9^{(')}$	$\sim (\bar{s}\gamma_\mu P_{L(R)} \bar{b}) (\ell\gamma^\mu \bar{\ell})$	
(A)	$C_{10}^{(')}$	$\sim (\bar{s}\gamma^\mu P_{L(R)} \bar{b}) (\ell\gamma_\mu \gamma_5 \bar{\ell})$	
Scalar	$C_S^{(')}$	$\sim (\bar{s}P_{R(L)} \bar{b}) (\ell\bar{\ell})$	
Pseudoscalar	$C_P^{(')}$	$\sim (\bar{s}P_{L(R)} \bar{b}) (\ell\gamma_5 \bar{\ell})$	

## Fully leptonic

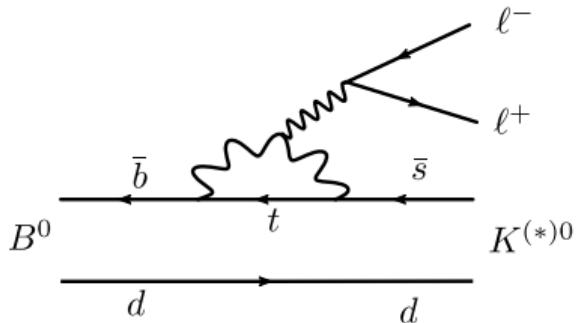


**Very rare!**  $\mathcal{B} \lesssim 10^{-9}$

- Theoretically clean
- Mostly clean to reconstruct

**Sensitive mainly to  $\mathcal{C}_{10}^{(')}$ .**

## Semi-leptonic

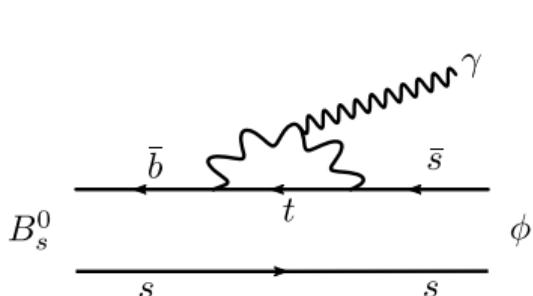


**Quite rare,**  $\mathcal{B} \sim 10^{-6}$

- Hadronic pollution.
- Mostly clean to reconstruct.
- Electron reconstruction very challenging.

**Sensitive to  $\mathcal{C}_7^{(')}$ ,  $\mathcal{C}_9^{(')}$  and  $\mathcal{C}_{10}^{(')}$  depending on  $q^2 \equiv m_{\ell^+\ell^-}^2$  region.**

## Radiative



**Fairly rare,**  $\mathcal{B} \sim 10^{-5}$

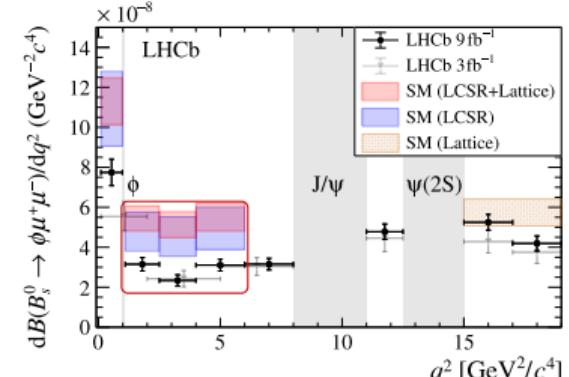
- Similar to semi-leptonic.
- Experimental resolution not great.

**Sensitive to  $\mathcal{C}_7^{(')}$ .**

# Anomalies of $b \rightarrow s\ell^+\ell^-$ decays

## Branching fractions

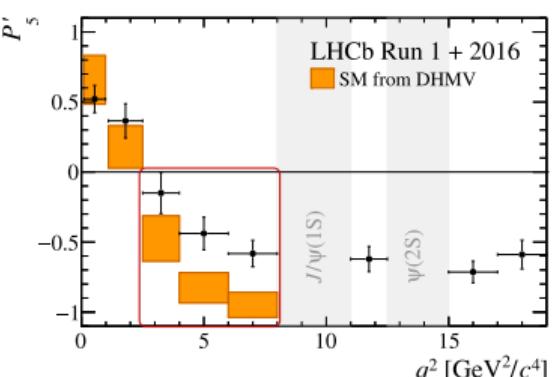
e.g.  $B_s^0 \rightarrow \phi \mu^+ \mu^-$



[PRL 127 (2021) 151801]

## Angular observables

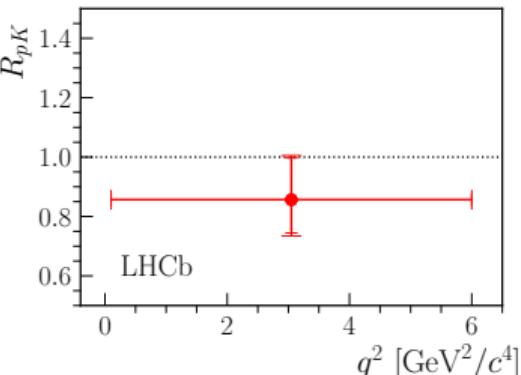
e.g.  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$



[PRL 125 (2020) 1, 011802]

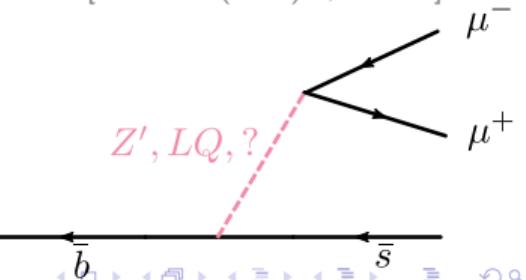
## Lepton universality ratios

e.g.  $\Lambda_b^0 \rightarrow \Lambda \ell^+ \ell^-$



[PRD 105 (2022) 1, 012010]

- Global  $b \rightarrow s\ell^+\ell^-$  fits prefer sizeable shifts in  $\mathcal{C}_{9,10}$  over their Standard Model values.
- New heavy particles could be responsible. Leptoquarks? New gauge bosons?



## 1 Fully leptonic decays

- Branching fractions
- Effective lifetimes

## 2 Semi-leptonic decays

- Branching fractions
- Angular analyses
- Lepton flavour universality ratios

## 3 Radiative decays

- Photon polarisation and  $CP$  violation

## 4 Global fits

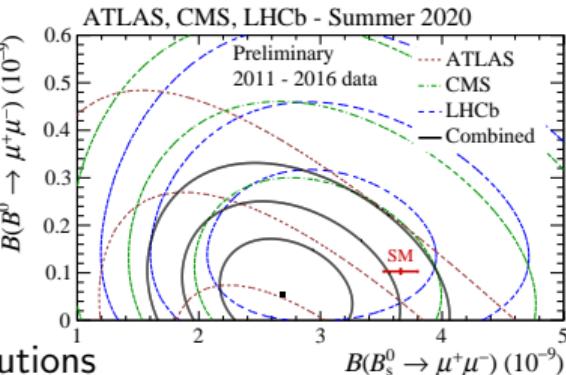
## 5 Summary

# $B_{(s)}^0 \rightarrow \mu^+ \mu^-$ branching fractions

Summer 2020 LHC  $B_{(s)}^0 \rightarrow \mu^+ \mu^-$  branching fraction combination

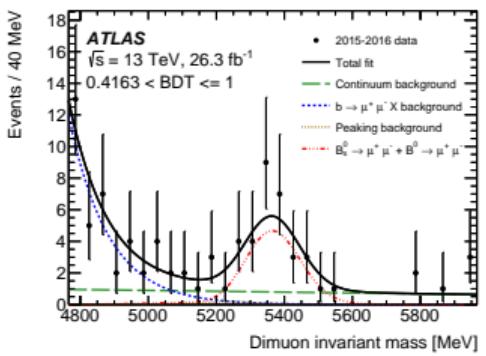
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9} \quad (2.4\sigma \text{ below SM})$$

[LHCb-CONF-2020-002]  
 [CMS-PAS-BPH-20-003]  
 [ATLAS-CONF-2020-049]

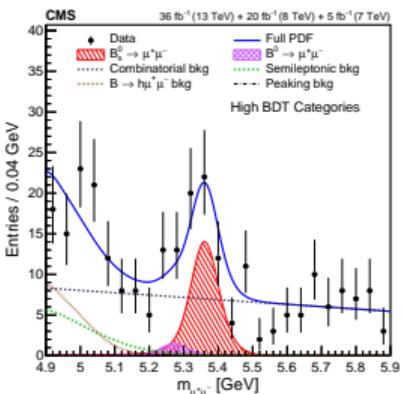


## Comparison of reconstructed $m_{\mu^+ \mu^-}$ distributions

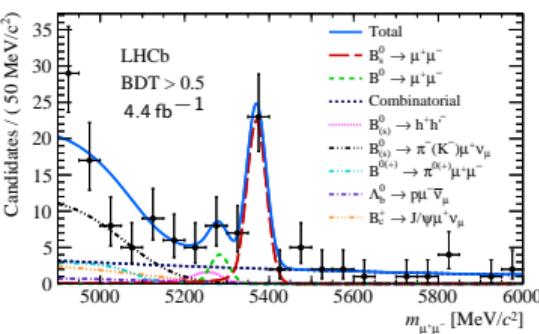
ATLAS [JHEP 04 (2019) 098]



CMS [JHEP 04 (2020) 188]



LHCb [PRL 118 (2017) 19, 191801]



# $B_{(s)}^0 \rightarrow \mu^+ \mu^-$ branching fractions

## 2022 LHC $B_{(s)}^0 \rightarrow \mu^+ \mu^-$ branching fraction combination

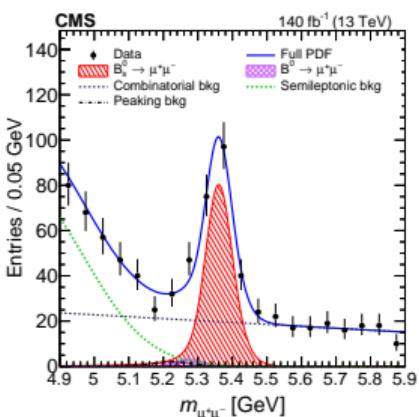
- Including the latest CMS and LHCb results gives: [arXiv:2210.07221]

$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.52^{+0.32}_{-0.30}) \times 10^{-9} \quad (0.4\sigma \text{ below SM})$$

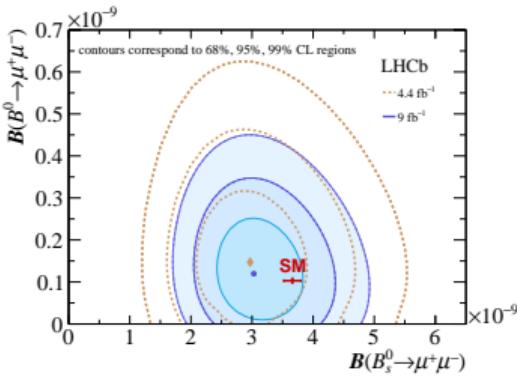
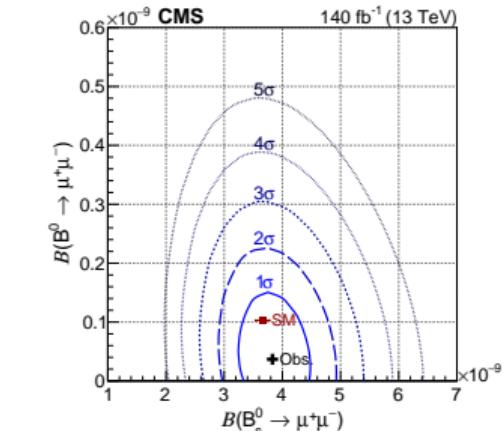
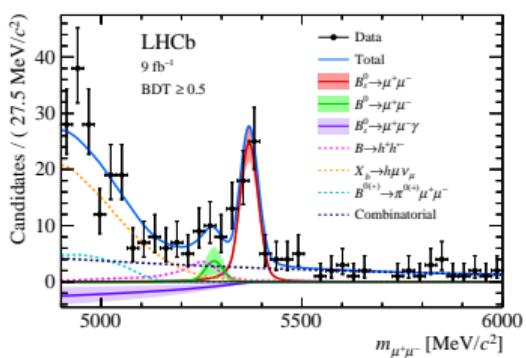
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$

## Comparison of reconstructed $m_{\mu^+ \mu^-}$ distributions

CMS [arXiv:2212.10311]



LHCb [PRD 105 (2022) 012010]



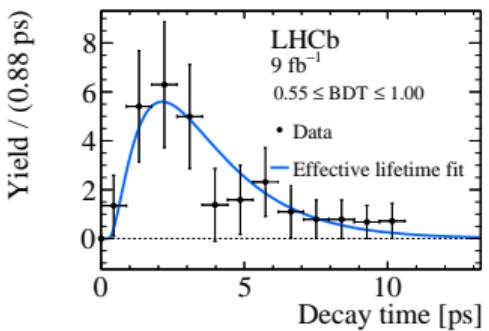
# $B_s^0 \rightarrow \mu^+ \mu^-$ effective lifetime

- The decay time distribution gives access to complementary information related to  $B_s^0$ - $\bar{B}_s^0$  mixing.
- The SM predicted *effective lifetime* is equal to that of the heavy  $B_s^0$  mass eigenstate: [PRL 109 (2012) 041801]

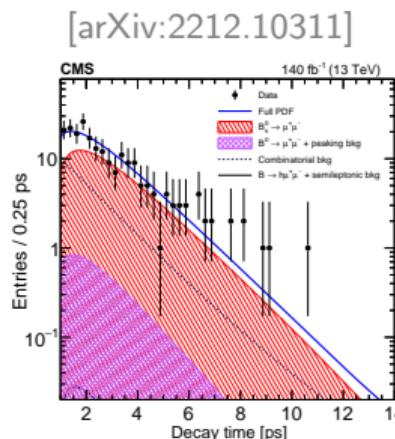
$$\tau_{\mu^+ \mu^-} \equiv \frac{\int_0^\infty t \Gamma(B_s^0(t) \rightarrow \mu^+ \mu^-) dt}{\int_0^\infty \Gamma(B_s^0(t) \rightarrow \mu^+ \mu^-) dt} \stackrel{\text{SM}}{=} \tau_H = 1.624 \pm 0.009$$

[PTEP 2022 (2022) 083C01]

[PRD 105 (2022) 012010]  
(Bkg. subtracted)



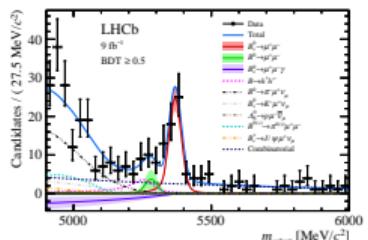
- Results are consistent with SM expectation of  $\tau_{\mu^+ \mu^-} = \tau_H$  at  $1.5\sigma$  (LHCb) and  $1\sigma$  (CMS).



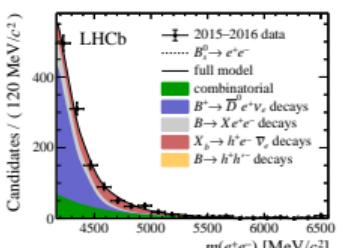
**LHCb:**  $\tau_{\mu^+ \mu^-} = 2.07 \pm 0.29 \text{ (stat.)} \pm 0.03 \text{ (syst.)} \text{ ps}$   
**CMS:**  $\tau_{\mu^+ \mu^-} = 1.83^{+0.23}_{-0.20} \text{ (stat.)}^{+0.04}_{-0.04} \text{ (syst.)} \text{ ps}$

# Related branching fraction limits

$B_s^0 \rightarrow \mu^+ \mu^- \gamma$  [PRD 105 (2022) 012010]  
ISR contribution in high  $q^2$  region.



$B_s^0 \rightarrow e^+ e^-$   
[PRL 124 (2020) 211802]



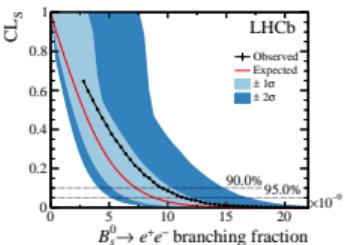
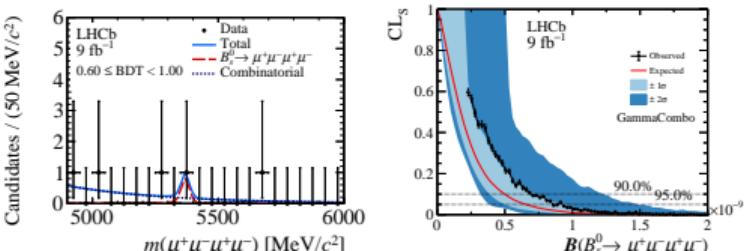
Standard Model predictions

$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma) = \mathcal{O}(10^{-9})$ , No reliable predictions at high  $q^2$

$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-) = (0.9\text{--}1.0) \times 10^{-10}$  [Phys. Atom. Nucl. 81 (2018) 347]

$\mathcal{B}(B_s^0 \rightarrow e^+ e^-) = (8.60 \pm 0.36) \times 10^{-14}$  [JHEP 10 (2019) 232]

$B_s^0 \rightarrow \mu^+ \mu^- \mu^+ \mu^-$  [JHEP 03 (2022) 109]  
fully non-resonant.



LHCb 95% confidence level limits

$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^- \gamma) < 2.0 \times 10^{-9}$

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

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

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# Observables in semi-leptonic decays

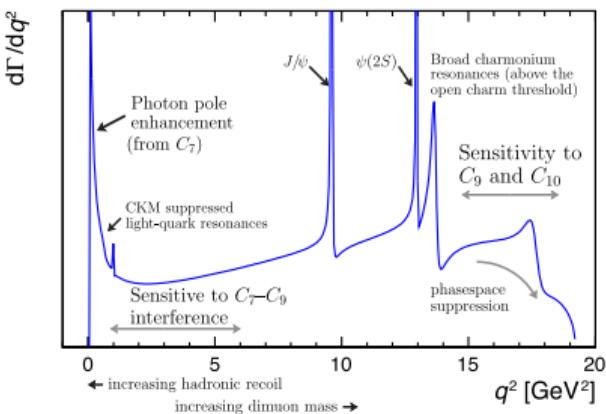
- Theoretically more challenging than fully leptonic decays due to the presence of final state hadrons.
- Observables accessible with current statistics include:

- Differential branching fractions.
- Angular observables.
- Lepton flavour universality (LFU) ratios.



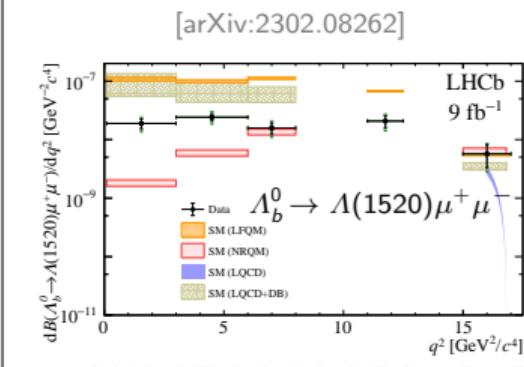
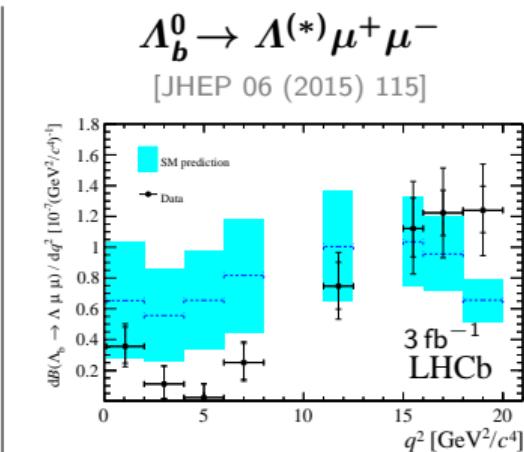
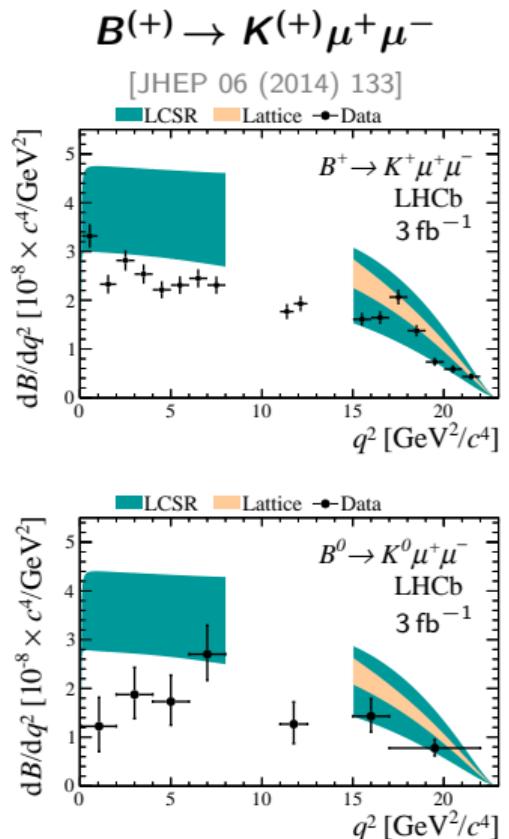
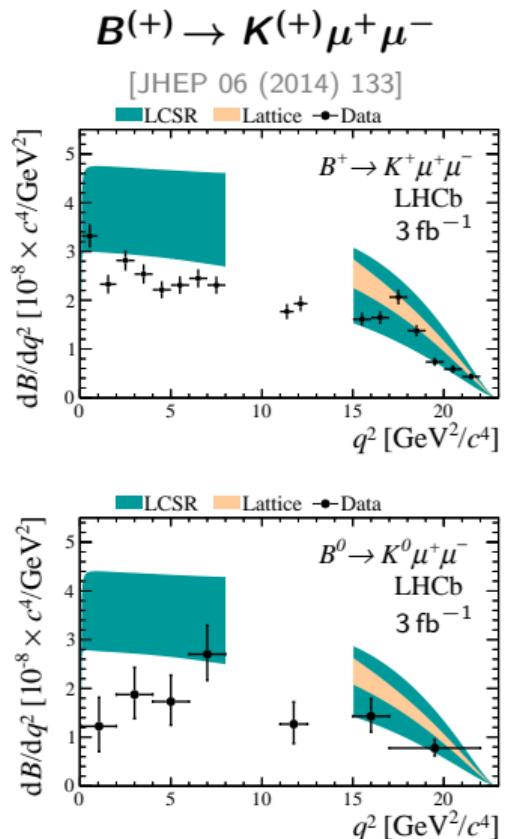
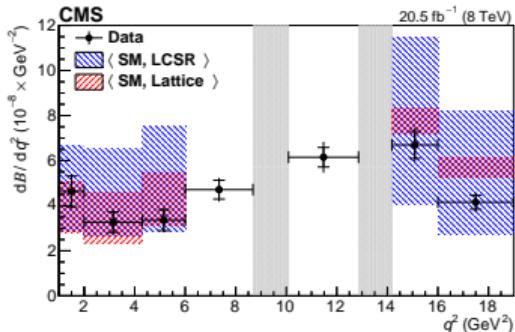
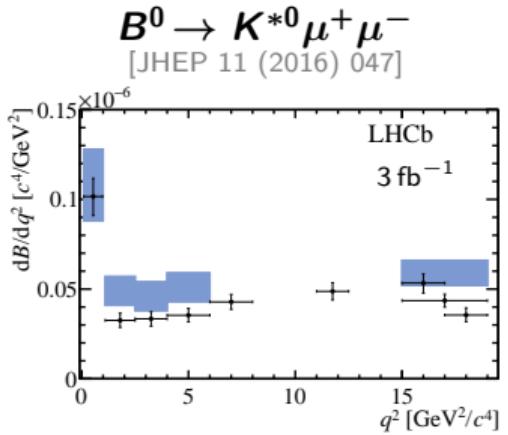
Increasing Standard Model precision

[Prog.Part.Nucl.Phys. 92 (2017) 50-91]

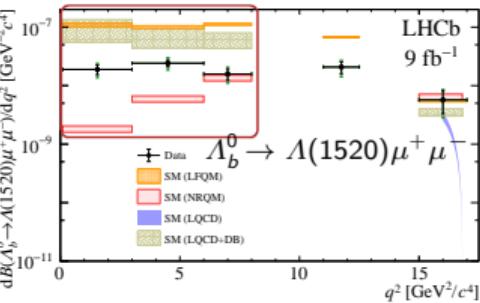
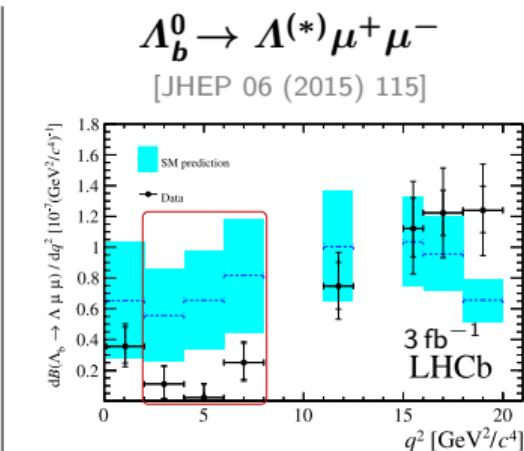
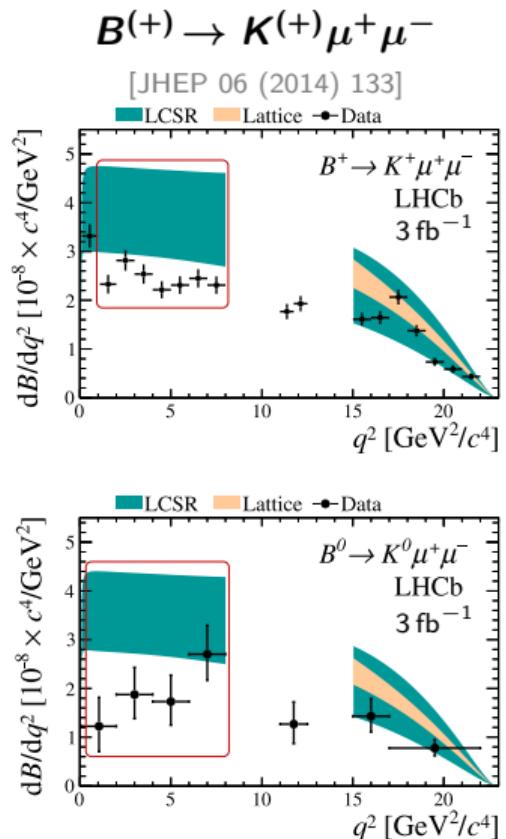
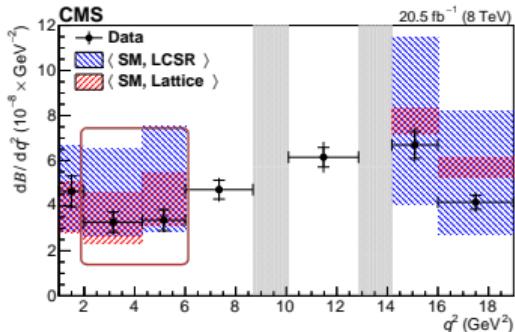
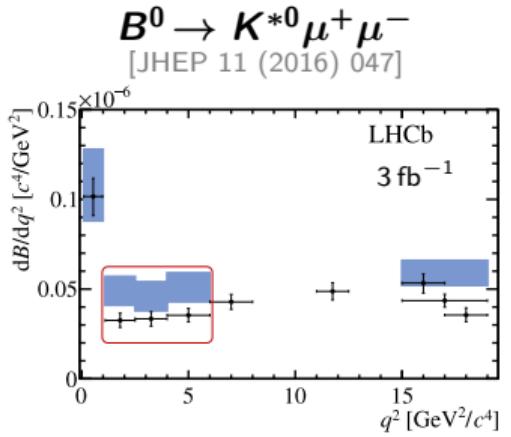


- Measurements made in bins of  $q^2$ , the dilepton invariant mass squared.
- Different  $q^2$  regions are sensitive to different effective operators.

# $b \rightarrow s \mu^+ \mu^-$ differential branching fractions



# $b \rightarrow s \mu^+ \mu^-$ differential branching fractions



- Semi-leptonic  $b \rightarrow s\ell^+\ell^-$  decays give access to numerous observables via their angular distribution — a function of the helicity angles (see diagram) and invariant masses in the decay.

$$\frac{d^4 \Gamma}{dq^2 d^3\Omega} = \frac{9}{32\pi} \sum_i J_i(q^2) f_i(\cos\theta_\ell, \cos\theta_K, \phi)$$

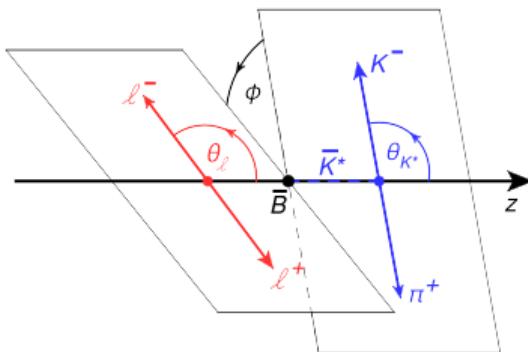
- The angular coefficients  $J_i$  are sensitive to NP in the Wilson Coefficients  $\mathcal{C}_{7,9,10}$ .
- $CP$ -averaged and  $CP$ -asymmetry observables:

$$S_i = \frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} (J_i + \bar{J}_i),$$

$$A_i = \frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} (J_i - \bar{J}_i)$$

- Optimised observables ( $F_L \equiv S_{1c}$ ):

$$P'_i = S_i / \sqrt{F_L(1 - F_L)}, \quad (i = 3, 4, 5)$$



The three helicity angles for the  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$  decay:  $\cos\theta_K$ ,  $\cos\theta_\ell$ ,  $\phi$ .

The decay is fully described by  $\cos\theta_K$ ,  $\cos\theta_\ell$ ,  $\phi$ , and  $q^2$ .

# Angular analyses of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

$$\begin{aligned}
 \frac{1}{d(\Gamma + \bar{\Gamma})q^2} \frac{d^3\Gamma}{d^3\Omega} &= \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\
 &\quad + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell - F_L \cos^2 \theta_K \cos 2\theta_\ell \\
 &\quad + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi \\
 &\quad + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell \\
 &\quad + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + S_8 \sin^2 \theta_K \sin 2\theta_\ell \sin \phi \\
 &\quad \left. + S_9 \sin^2 \theta_K \sin 2\theta_\ell \sin 2\phi \right]
 \end{aligned}$$

$$P'_5 = S_5 / \sqrt{F_L(1 - F_L)}$$

ATLAS

Belle

CMS

LHCb

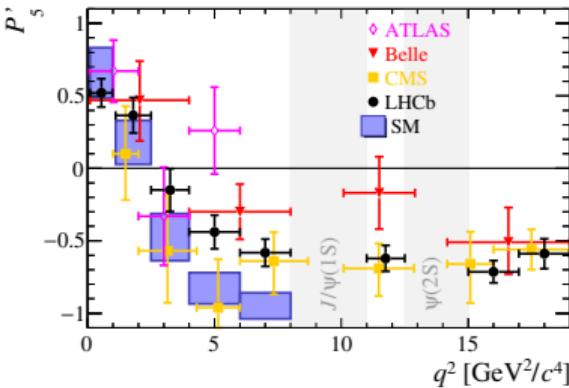
SM

CMS:[PLB 781 (2018) 517-541]

ATLAS:[JHEP 10 (2018) 047]

LHCb:[PRL 125 (2020) 1, 011802]

Belle:[PRL 118 (2017) 11, 111801]



[Prog.Part.Nucl.Phys. 120 (2021) 103885]

**Notable deviation from SM in  $P'_5$  observed at central  $q^2$  by both LHCb and ATLAS.**

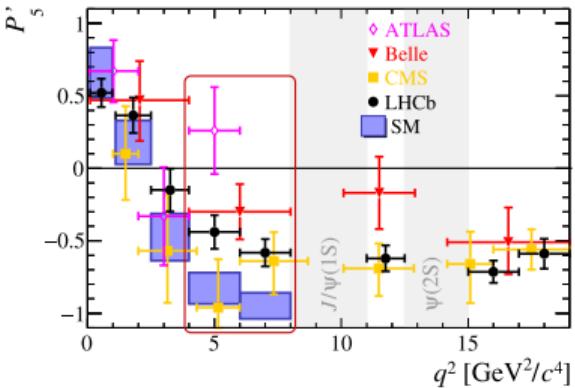
# Angular analyses of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

$$\frac{1}{d(\Gamma + \bar{\Gamma})q^2} \frac{d^3\Gamma}{d^3\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\ \left. + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell - F_L \cos^2 \theta_K \cos 2\theta_\ell \right. \\ \left. + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi \right. \\ \left. + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell \right. \\ \left. + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + S_8 \sin^2 \theta_K \sin 2\theta_\ell \sin \phi \right. \\ \left. + S_9 \sin^2 \theta_K \sin 2\theta_\ell \sin 2\phi \right]$$

$$P'_5 = S_5 / \sqrt{F_L(1 - F_L)}$$

LHCb reports local tensions of  $2.5\sigma$  and  $2.9\sigma$  in  $P'_5$  in the  $[4, 6]$  and  $[6, 8] \text{ GeV}^2/c^4$   $q^2$  bins, respectively. ATLAS reports a  $2.7\sigma$  tension for the  $[4, 6] \text{ GeV}^2/c^4$  bin.

CMS:[PLB 781 (2018) 517-541]  
ATLAS:[JHEP 10 (2018) 047]  
LHCb:[PRL 125 (2020) 1, 011802]  
Belle:[PRL 118 (2017) 11, 111801]



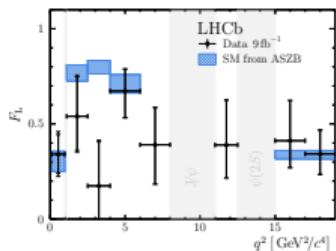
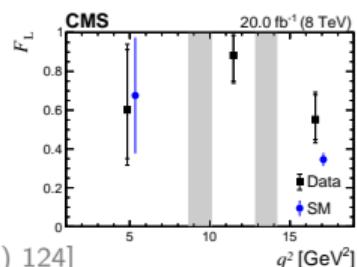
[Prog.Part.Nucl.Phys. 120 (2021) 103885]

**Notable deviation from SM in  $P'_5$  observed at central  $q^2$  by both LHCb and ATLAS.**

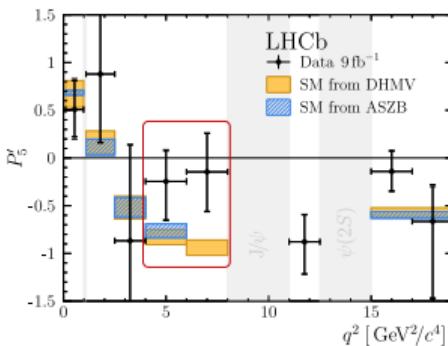
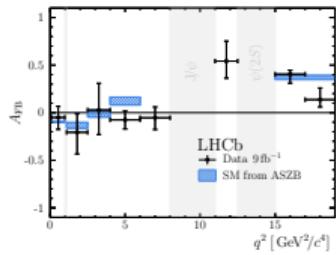
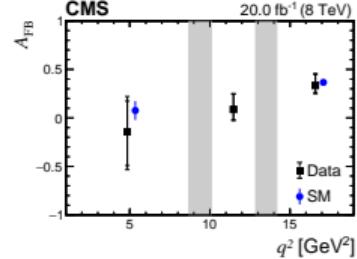
# Angular analyses of $B^+ \rightarrow K^{*+} \mu^+ \mu^-$

Angular analyses are also performed for the isospin partner decay ,  $B^+ \rightarrow K^{*+}$

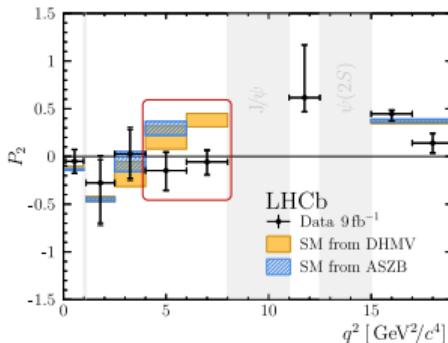
- LHCb results show similar trends in  $P'_5$ , and an additional deviation in  $P_2 \equiv \frac{2}{3} A_{FB} / (1 - F_L)$ , ( $A_{FB} \equiv \frac{3}{4} S_{6S}$ ).
- CMS measured  $F_L$  and  $A_{FB}$  and found them to be consistent with both LHCb measurements and the Standard Model.



[JHEP 04 (2021) 124]

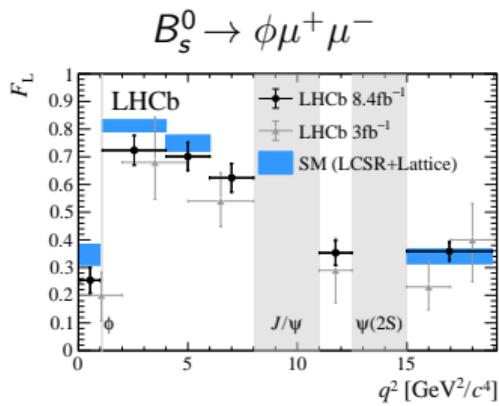


[PRL 126 (2021) 16, 161802]



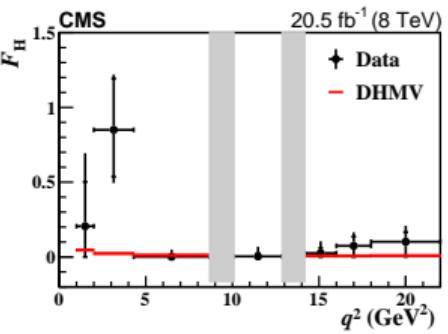
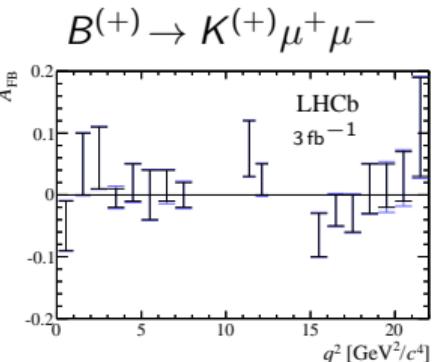
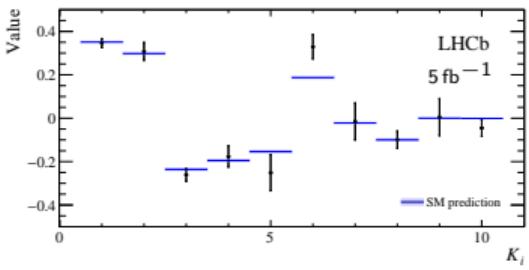
# More angular analyses...

- Angular analyses are performed in other semi-leptonic channels too resulting in a *huge* set of observables to test the SM.
- Slight tensions observed in some — e.g.  $F_L$  in  $B_s^0 \rightarrow \phi \mu^+ \mu^-$  (left);  $K_6$  in  $\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$  (centre).



$b \rightarrow s \mu^+ \mu^-$  measurements at LHCb  
also covered in talk by J. Reich.

$\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$



- Lepton flavour universality (LFU) is an *assumption* of the Standard Model.
- LFU can be tested through ratios of branching fractions involving different lepton generations, e.g.

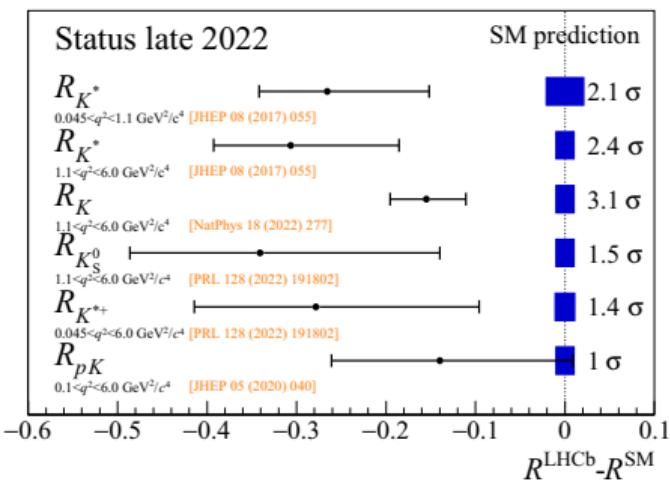
$$R_X = \frac{\mathcal{B}(B \rightarrow X \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow X e^+ e^-)}$$

- **Negligible theoretical uncertainty.**
- Studied extensively in  $b \rightarrow s \ell^+ \ell^-$  decays at LHCb.
- Experimentally measured as a double ratio to cancel systematics:

$$R_X = \frac{\mathcal{B}(B \rightarrow X \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow X e^+ e^-)} \Big/ \frac{\mathcal{B}(B \rightarrow X J/\psi (\rightarrow \mu^+ \mu^-))}{\mathcal{B}(B \rightarrow X J/\psi (\rightarrow e^+ e^-))}$$

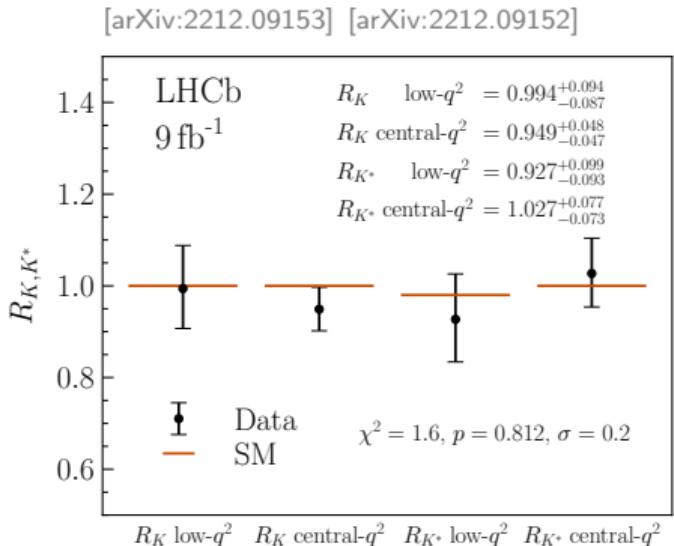
- Up until late 2022, consistent deviations from SM predictions in LHCb  $R_X$  ratios.
- Largest deviation in  $R_K$  which reached  $3.1\sigma$ .

See talk by S. Schmitt for more details on LFU at LHCb.



# Current status of LFU in $b \rightarrow s\ell^+\ell^-$ decays

- Simultaneous measurement of  $R_K$  and  $R_{K^*}$  by LHCb in Dec 2022 supersedes previous measurements.
- **Latest results are consistent with the SM at  $0.2\sigma$**  — no sign of LFU violation.
- Extensive crosschecks, e.g.:
  - measuring resonant  $r_{J/\psi}$  (single ratio) and  $R_{\psi(2S)}$ .
  - stability with respect to PID criteria.
- Shift in new  $R_K$  results is partly statistical, but mostly systematic in electron mode:
  - ① Reduction in misidentified hadronic backgrounds.
  - ② Explicit modelling of residual misidentified hadronic backgrounds.
- Most precise test of LFU in  $b \rightarrow s\ell^+\ell^-$  decays.



low  $q^2$ :  $0.1 < q^2 < 1.1 \text{ GeV}^2/c^4$   
central  $q^2$ :  $1.1 < q^2 < 6.0 \text{ GeV}^2/c^4$

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## 4 Global fits

## 5 Summary

# Photon polarisation in radiative decays

- Right(left)-handed photons in  $\overset{(-)}{b} \rightarrow \overset{(-)}{s}\gamma$  decays are suppressed in the SM due to V-A structure of weak interaction,  $\mathcal{C}'_7 \approx \frac{m_s}{m_b} \mathcal{C}_7$ .
- The time dependent decay rate for  $B_q^0 \rightarrow M^0\gamma$  or  $\bar{B}_q^0 \rightarrow M^0\gamma$  is given by:

$$\Gamma(t) \propto e^{-\Gamma_q t} \left[ \cosh(\Delta\Gamma_q t/2) - A^\Delta \sinh(\Delta\Gamma_q t/2) + \zeta C \cos(\Delta m_q t) - \zeta S \sin(\Delta m_q t) \right]$$

with  $\zeta = 1$  ( $-1$ ) for an initial  $B_q$  ( $\bar{B}_q$ ).

- The coefficient  $C$  quantifies direct  $CP$  violation ( $CPV$ ) in the decay, whilst the mixing-induced  $A^\Delta$  and  $S$  observables are sensitive to the photon polarisation.

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- The coefficient  $C$  quantifies direct  $CP$  violation ( $CPV$ ) in the decay, whilst the mixing-induced  $A^\Delta$  and  $S$  observables are sensitive to the photon polarisation.

- LHCb has measured these observables in a time-dependent tagged analysis of  $B_s^0 \rightarrow \phi\gamma$ .
- Results are in agreement with the SM predictions [PLB 664 (2008) 174-179].
- No evidence for enhancement of right-handed photons.

Photon polarisation and  $CPV$  in  $B_s^0 \rightarrow \phi\gamma$

**LHCb results:** [PRL 123 (2019) 8, 081802]

$$A_{\phi\gamma}^\Delta = -0.67^{+0.37}_{-0.41} \text{ (stat.)} \pm 0.17 \text{ (syst.)}$$

$$C_{\phi\gamma} = 0.11 \pm 0.29 \text{ (stat.)} \pm 0.11 \text{ (syst.)}$$

$$S_{\phi\gamma} = 0.43 \pm 0.30 \text{ (stat.)} \pm 0.11 \text{ (syst.)}$$

- At low  $q^2$ , the  $B^0 \rightarrow K^{*0} e^+ e^-$  decay is dominated by virtual photon contributions from  $\mathcal{C}_7^{(')}$ .
- The angular distribution at very low  $q^2$  simplifies to four observables:  $F_L$ ,  $A_T^{\text{Re}} \equiv 2P_2$ ,  $A_T^{(2)} \equiv P_1$ ,  $A_T^{\text{Im}} \equiv -2P_3^{CP}$ .
- $A_T^{(2)}$  and  $A_T^{\text{Im}}$  are sensitive to the virtual photon polarisation.

## Angular observables in $B^0 \rightarrow K^{*0} e^+ e^-$

**LHCb results** for  $q^2 \in [0.0008, 0.257] \text{ GeV}^2/c^4$ :

$$F_L = 0.044 \pm 0.026 \text{ (stat.)} \pm 0.014 \text{ (syst.)}$$

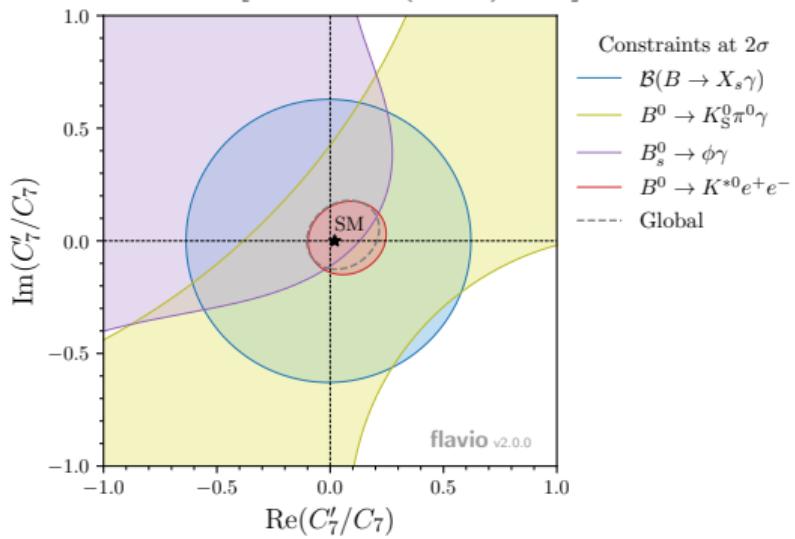
$$A_T^{\text{Re}} = -0.06 \pm 0.08 \text{ (stat.)} \pm 0.02 \text{ (syst.)}$$

$$A_T^{(2)} = +0.11 \pm 0.10 \text{ (stat.)} \pm 0.02 \text{ (syst.)}$$

$$A_T^{\text{Im}} = +0.02 \pm 0.10 \text{ (stat.)} \pm 0.01 \text{ (syst.)}$$

- Compatible with Standard Model predictions.
- Currently the strongest constraints on contributions from right-handed photons.

[JHEP 12 (2020) 081]



# Photon polarisation in radiative baryonic decays

- The baryonic decay  $\Lambda_b^0 \rightarrow \Lambda(\rightarrow p\pi^-)\gamma$  allows a direct measurement of the photon polarisation parameter,  $\alpha_\gamma \equiv (\gamma_L - \gamma_R)/(\gamma_L + \gamma_R)$ , via its angular distribution:

$$\frac{d\Gamma}{d\cos\theta_p} \propto 1 - \alpha_\Lambda \alpha_\gamma \cos\theta_p.$$

$\theta_p$  is the angle between the proton and  $-\Lambda_b^0$  momenta.

$\alpha_\gamma$  is expected to be  $\approx 1$  (-1) for the  $b$  ( $\bar{b}$ ) decay in the SM.

## Photon polarisation in $\Lambda_b^0 \rightarrow \Lambda\gamma$

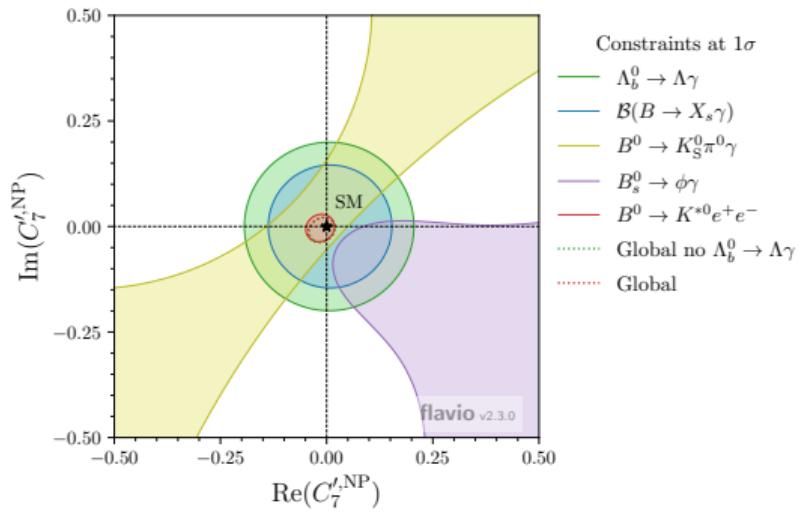
**LHCb results** [PRD 105 (2022) 5, L051104]:

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

$$\alpha_\gamma^- > 0.56 \text{ (0.44) at 90\% (95\%) C.L. } (\Lambda_b^0)$$

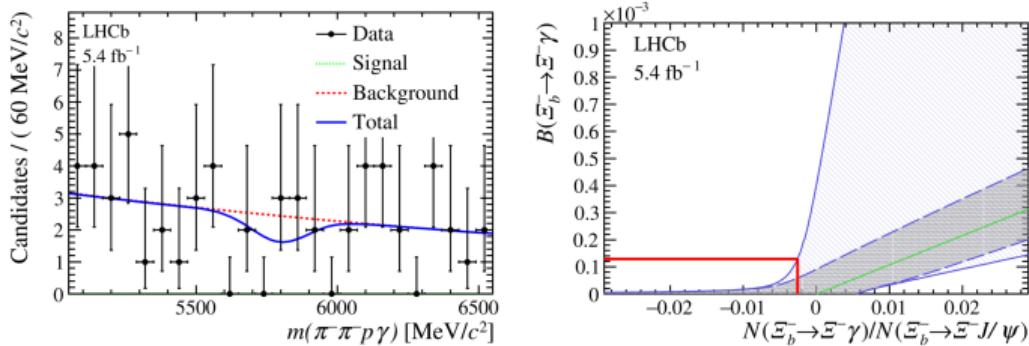
$$\alpha_\gamma^+ = -0.56^{+0.36}_{-0.33} \text{ (stat.)}^{+0.16}_{-0.09} \text{ (syst.) } (\bar{\Lambda}_b^0)$$

- Consistent at  $1\sigma$  with SM prediction of 1 for  $\alpha_\gamma$ .
- Consistent with  $CP$  symmetry,  $\alpha_\gamma^- = -\alpha_\gamma^+$ .



# Other radiative decay searches

- LHCb searched for the  $\Xi_b^- \rightarrow \Xi^- \gamma$  decay. No signal was observed and a limit was set.



**LHCb 95% (90%) confidence level limit:**

$$\mathcal{B}(\Xi_b^- \rightarrow \Xi^- \gamma) < 1.3(0.6) \times 10^{-4} \quad [\text{JHEP } 01 (2022) 069]$$

- This limit is in tension with some LCSR calculations which predict a value of  $\mathcal{B}(\Xi_b^- \rightarrow \Xi^- \gamma) = 3.03 \pm 0.10 \times 10^{-4}$  [PRD 83 (2011) 054007].
- Consistent with estimation from flavour symmetry arguments which predict  $\mathcal{B}(\Xi_b^- \rightarrow \Xi^- \gamma) = 1.23 \pm 0.64 \times 10^{-5}$  [J.Phys.G 48 (2021) 8, 085001].

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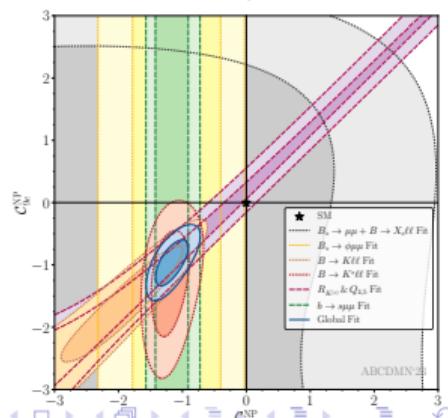
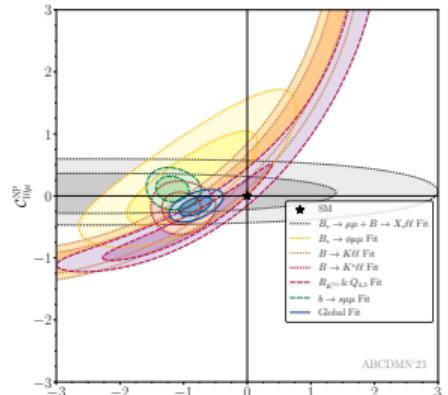
- Photon polarisation and  $CP$  violation

## 4 Global fits

## 5 Summary

Stay tuned for a full talk by B. Capdevila on the status of global fits.

- Prior to 2022, global  $b \rightarrow s\ell^+\ell^-$  fits were favoured LFU violating New Physics in  $\mathcal{C}_{9\mu}$  and possibly  $\mathcal{C}_{10\mu}$ .
- Implications of 2022  $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$  and  $R_{K^{(*)}}$  updates [arXiv:2304.07330]:
  - ① NP in  $\mathcal{C}_{9\mu}$  *only* now favoured over  $\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$ , due to SM-like  $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$ .
  - ② *Lepton flavour universal* NP in  $\mathcal{C}_{9\ell}$  now favoured over LFU violation or right-handed currents — provides optimal fit data due to SM-like  $R_{K^{(*)}}$ .
- The interpretation of the  $b \rightarrow s\ell^+\ell^-$  anomalies is now more dependent on our understanding of hadronic uncertainties.
- Improved experimental precision is more important than ever!



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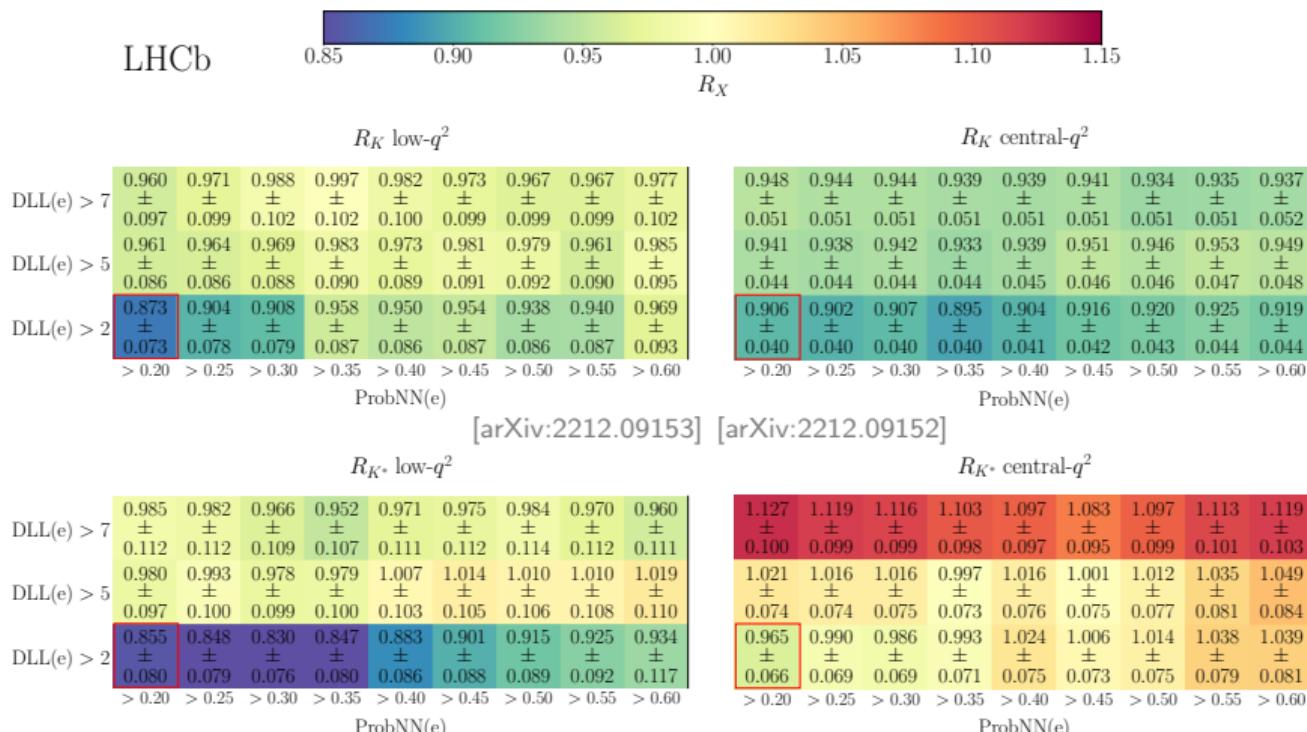
- Numerous experimental anomalies exist  $b \rightarrow s\ell^+\ell^-$  decays.
- Recent results on  $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$  and  $R_{K^{(*)}}$  are in agreement with Standard Model predictions.
- Anomalies in other  $b \rightarrow s\ell^+\ell^-$  observables are unaffected!
- Lepton flavour universal New Physics in  $\mathcal{C}_9$  is now preferred over LFU violation.
- All measurements remain statistically limited — further updates from LHC exploiting Run 3 luminosities are essential to improve precision.

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Thank you for your attention!

# Backup

# PID dependence of $R_{K,K^*}$

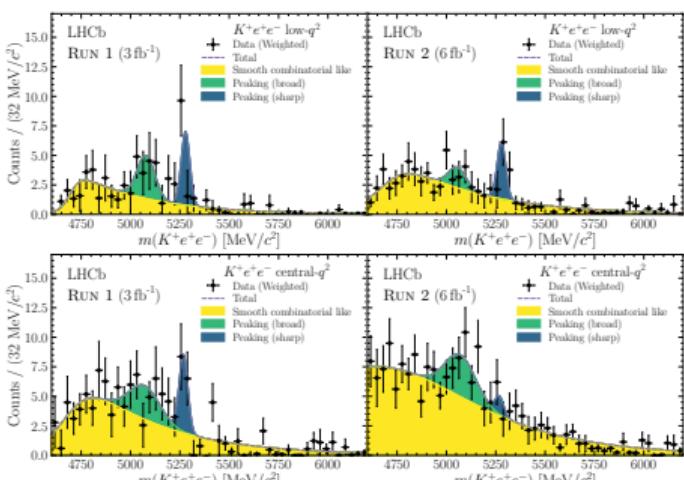
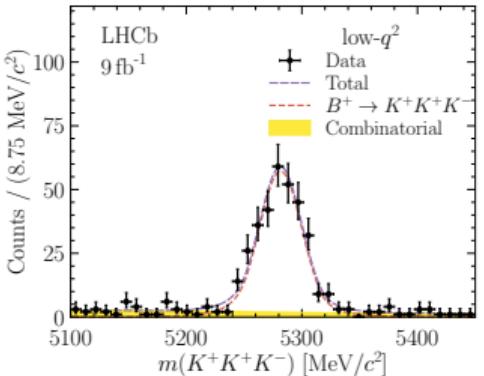
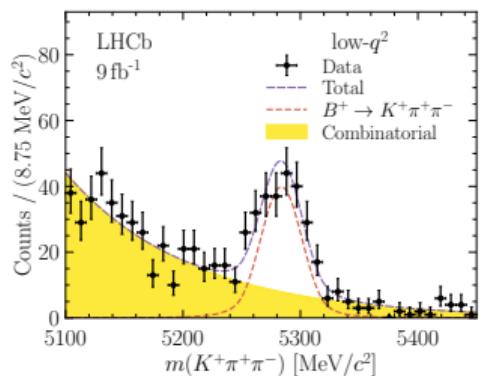


- When misidentified hadronic backgrounds are ignored, varying electron PID cuts shows a clear correlation with the  $R_{K,K^*}$  central value.

# Residual background modelling in $R_{K^{(*)}}$

- Dominant misID backgrounds,  $B^+ \rightarrow K^+\pi^+\pi^-$  and  $B^+ \rightarrow K^+K^+K^-$ , are mostly removed by tighter PID.

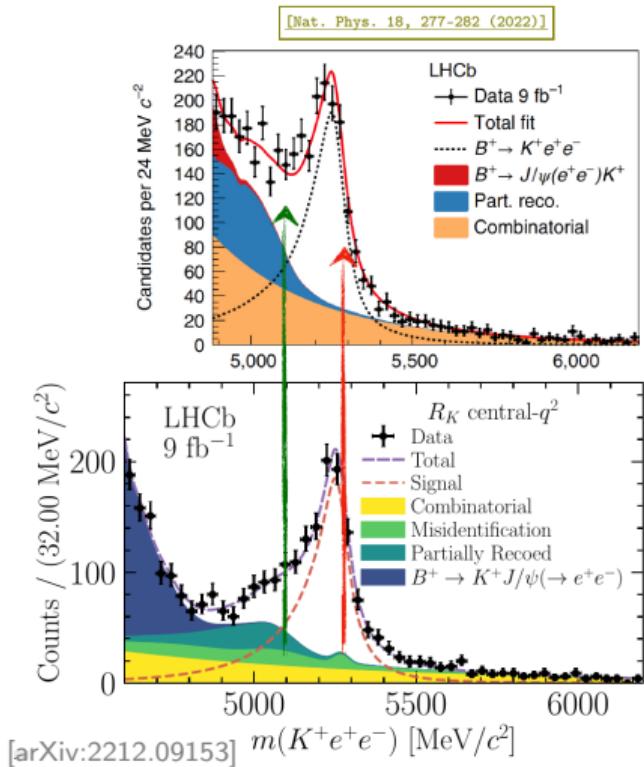
[arXiv:2212.09153] [arXiv:2212.09152]



- Residual contributions modelled via control regions in data with inverted electron PID requirements.
  - Full reco. double misID (both electrons in control region) backgrounds are straightforward to model.
  - Single misID and/or partial reco. backgrounds also contribute with more complex shapes.
- Yields extrapolated to signal regions using PID calibration samples.

# Comparison with previous $R_K$

Credit: R. Quagliani



- ◆ Different PID cut used → Allowed  $\sigma_{\text{stat}}$  :  $\pm 0.033$
- ◆ Mis-ID rate from  $D^{*-} \rightarrow D^0(K\pi)\pi$
- ◆ With new(previous) analysis requirements

Sample	$\pi \rightarrow e$	$K \rightarrow e$
(11+12)	RUN 1	1.78 (1.70) %
(15+16)	RUN 2P1	0.83 (1.51) %
(17+18)	RUN 2P2	0.80 (1.50) %
		0.69 (1.24) %
		0.18 (1.25) %
		0.16 (1.23) %

single-misID	$\times 1$ (Run1)	$\times 2$ (Run1)
	$\times 2$ (Run2)	$\times 7$ (Run2)
double-misID	$\times 1^2$ (Run1)	$\times 2^2$ (Run1)
	$\times 2^2$ (Run2)	$\times 7^2$ (Run2)

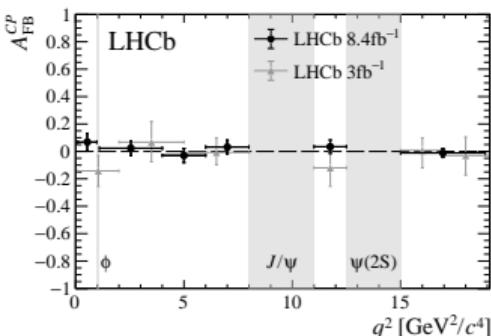
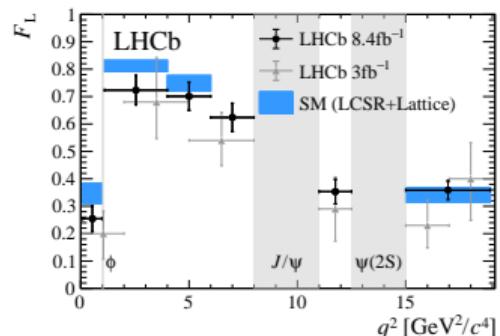
- ◆ Shift due to contamination at looser working point : **+0.064**
- ◆ Shift due to not inclusion of background in mass fit: **+0.038**

Adds linearly

# Angular analyses of $B_s^0 \rightarrow \phi\mu^+\mu^-$

- Experimentally,  $B_s^0 \rightarrow \phi\mu^+\mu^-$  is reconstructed via  $\phi \rightarrow K^+K^-$ , thus the final state is *not* self-tagging.
  - Reduced set of accessible observables in untagged rate (in particular, **no access to  $S_5$  or  $A_{FB}$  and hence no access to  $P_2$  or  $P'_5$** ).
- $CP$  asymmetry versions of those observables are measured instead.

- Generally good agreement with SM.
- Slight tension in  $F_L$  at low  $q^2$ .
- All  $CP$  asymmetry observables, including  $A_{FB}^{CP}$ , are consistent with SM expectation of zero.



LHCb 8.4  $\text{fb}^{-1}$ : [JHEP 11 (2021) 043]

LHCb 3.0: [JHEP 09 (2015) 179]

# Angular analyses of $B \rightarrow K\mu^+\mu^-$

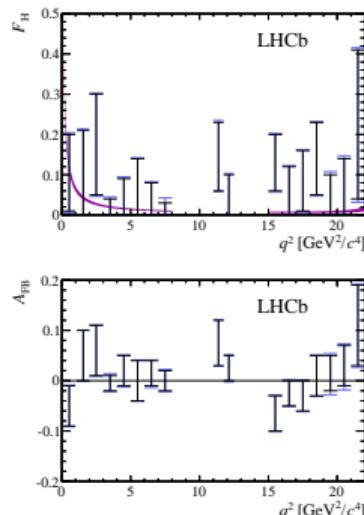
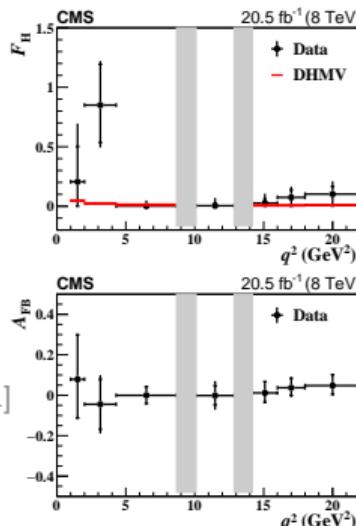
- Angular analyses are also performed for the pseudoscalar  $K^+$  and  $K_S^0$  final states.
- The angular distribution is much simpler, providing just two observables,  $F_H$  and  $A_{FB}$ :

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_\ell} = \frac{3}{4} (1 - F_H) (1 - \cos^2 \theta_I) + \frac{1}{2} F_H + A_{FB} \cos \theta_\ell$$

- The  $K_S^0 \rightarrow \pi^+ \pi^-$  decay is not self-tagging and thus only  $A_{FB}^{CP}$  is accessible — analysis is done in  $|\cos \theta_\ell|$  such that only  $F_H$  can be non-zero.

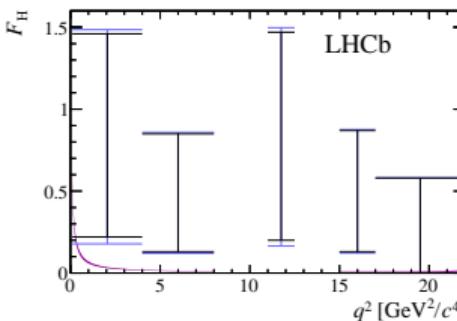
$B^+ \rightarrow K^+ \mu^+ \mu^-$

[PRD 98 (2018) 11, 112011]  
[JHEP 05 (2014) 082]



No significant deviations from SM predictions are observed in either decay.

$B^0 \rightarrow K_S^0 \mu^+ \mu^-$



# Angular analyses of $\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$

- The  $\Lambda_b^0$  can be produced polarised, giving a total of 34 angular observables.
- Observables typically extracted via a *moments analysis*:

$$\frac{d^5\Gamma}{d\vec{\Omega}} = \frac{3}{32\pi^2} \sum_{i=1}^{34} K_i f_i(\vec{\Omega}), \quad K_i = \sum_n w_n g_i(\vec{\Omega}) / \sum_n w_n,$$

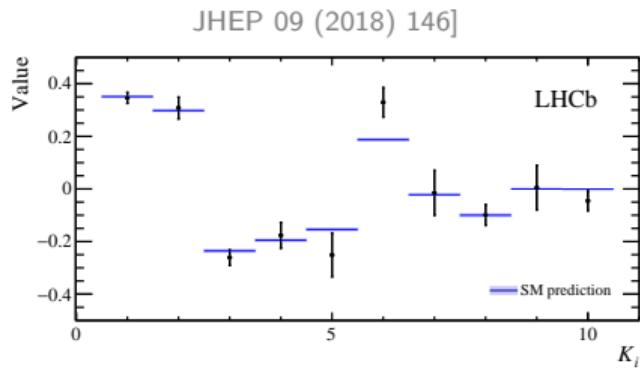
$w_n \equiv$  efficiency corrected and background subtracted number of candidates.

- Observables  $K_1-K_{10}$  are consistent with SM predictions.
- Largest deviation in  $K_6$  at  $2.6\sigma$  from the SM.
- Polarisation dependent observables  $K_{11}-K_{34}$  are consistent with zero and thus with small/no  $\Lambda_b^0$  polarisation.

$$A_{FB}^\ell = \frac{3}{2} K_3 = -0.39 \pm 0.04 \text{ (stat.)} \pm 0.01 \text{ (syst.)}$$

$$A_{FB}^h = K_4 + \frac{1}{2} K_5 = -0.30 \pm 0.05 \text{ (stat.)} \pm 0.02 \text{ (syst.)}$$

$$A_{FB}^{\ell h} = \frac{3}{4} K_6 = +0.25 \pm 0.04 \text{ (stat.)} \pm 0.01 \text{ (syst.)}$$



# Amplitude analysis of $B^+ \rightarrow K^+ \mu^+ \mu^-$

- To cross check theoretical assumptions on the size of charm-loop contributions, LHCb performed an amplitude analysis of the  $B^+ \rightarrow K^+ \mu^+ \mu^-$  decay in 538 bins across the full  $q^2$  domain.
- The analysis used an isobar approach to explicitly model the **non-local amplitudes** and measured their phase differences with respect to the local penguin amplitudes.

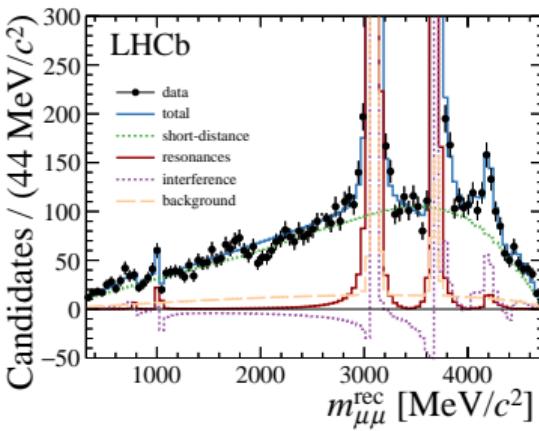
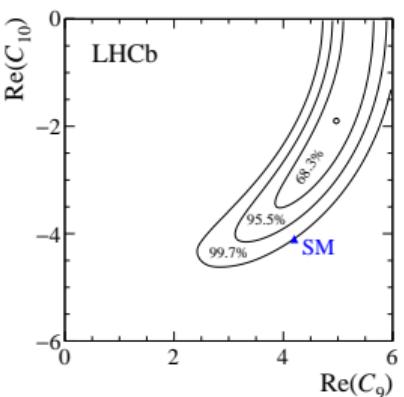
[Eur.Phys.J.C 77 (2017) 3, 161]

$$\frac{d\Gamma}{dq^2} = \mathcal{N}|\vec{k}|\beta \left[ \frac{2}{3}|\vec{k}|^2\beta^2|\mathcal{C}_{10}f_+(q^2)|^2 + \frac{4m_\mu^2(m_B^2 - m_K^2)^2}{q^2m_B^2}|\mathcal{C}_{10}f_0(q^2)|^2 \right. \\ \left. + |\vec{k}|^2 \left(1 - \frac{1}{3}\beta^2\right) \left| \mathcal{C}_9^{\text{eff}}(q^2)f_+(q^2)|^2 + 2\mathcal{C}_7 \frac{m_b + m_s}{m_B + mK} f_T(q^2) \right|^2 \right],$$

$$\mathcal{C}_9^{\text{eff}}(q^2) = \mathcal{C}_9 + \sum_{j \in \{\omega, \dots, \psi(4415)\}} \eta_j e^{i\delta_j} A_j^{\text{res}}(q^2).$$

Integrated branching fraction compatible with previous measurements:

$$\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-) = (4.37 \pm 0.15 \text{ (stat.)} \pm 0.23 \text{ (syst.)}) \times 10^{-7}$$



**Best fit values for  $\mathcal{C}_9$  and  $\mathcal{C}_{10}$  deviate from the SM at  $3\sigma$ .**

⇒ non-local interference disfavoured to explain  $B^+ \rightarrow K^+ \mu^+ \mu^-$  BF anomaly.

- LHCb has measured the ratio of branching fractions [Nucl.Phys.B 867 (2013) 1-18]

$$\frac{\mathcal{B}(B_s^0 \rightarrow \phi\gamma)}{\mathcal{B}(B^0 \rightarrow K^{*0}\gamma)} = 1.23 \pm 0.06 \text{ (stat.)} \pm 0.04 \text{ (syst.)} \pm 0.10 \text{ (} f_s/f_d \text{).}$$

- Corresponds to  $\mathcal{B}(B_s^0 \rightarrow \phi\gamma) = (3.5 \pm 0.4) \times 10^{-5}$ .

- Both results in agreement with previous measurements [PRL 100 (2008) 121801] and SM predictions [Eur.Phys.J.C 55 (2008) 577-595] at  $< 2\sigma$ .

- The direct  $CP$  asymmetry was also measured in  $B^0 \rightarrow K^{*0}\gamma$  by LHCb:

$$\mathcal{A}_{CP}(B^0 \rightarrow K^{*0}\gamma) = (0.8 \pm 1.7 \text{ (stat.)} \pm 0.9 \text{ (syst.)})\%,$$

in agreement with the SM at  $< 1\sigma$ .

