UNIVERSITY OF CAMBRIDGE

Latest results on $b \to s\ell\ell$ decays at LHCb

LHC EFT WG meeting

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with a lot of material from M. Santimaria, T. Mombächer, K. Petridis

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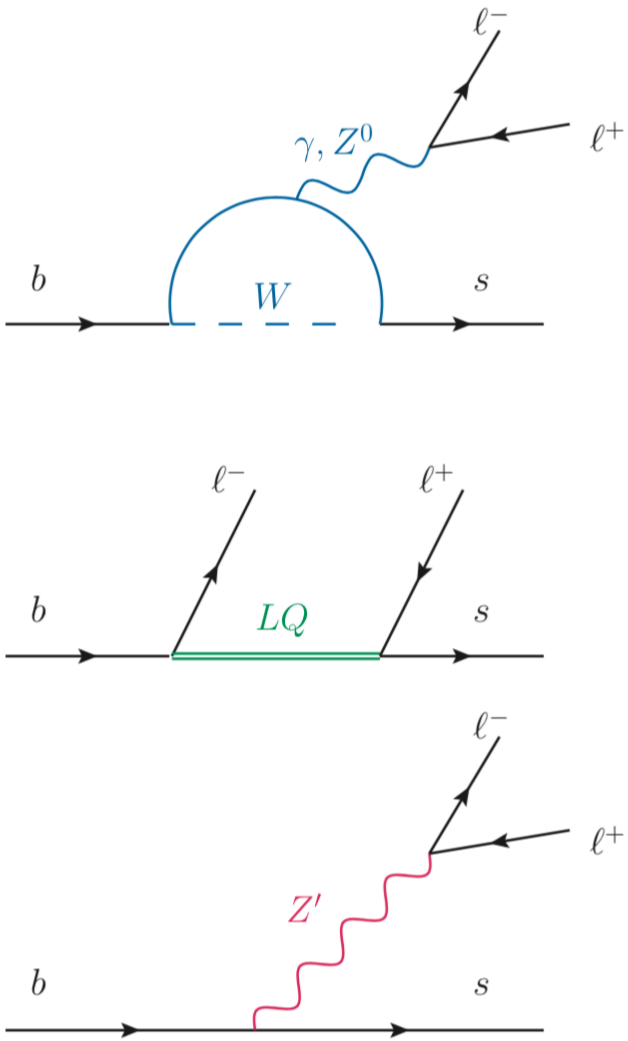
Why $b \to s\ell\ell$ decays?

They are Flavour Changing Neutral Current transitions and are therefore suppressed in the SM.

- This is not necessarily true in a New Physics scenario.

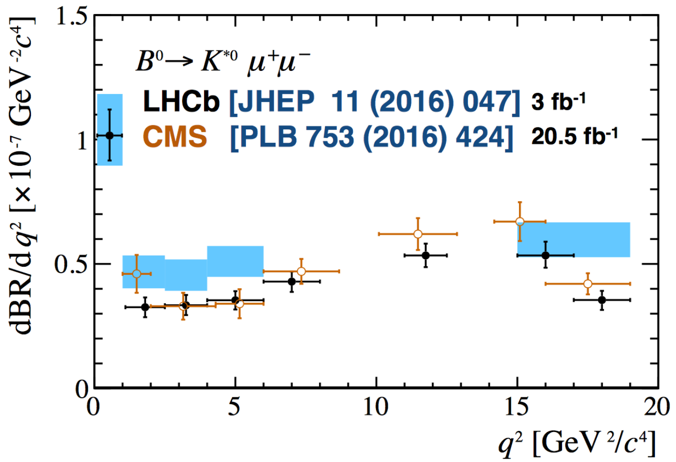
NP could affect different kinds of observables,

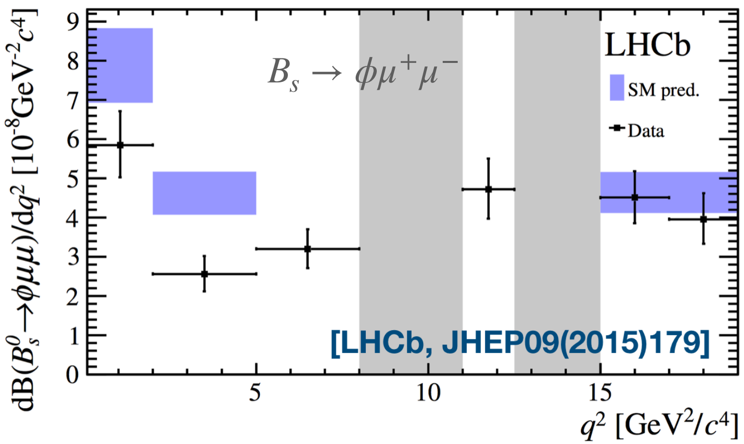
- Branching ratios
- Angular observables
- Lepton Flavour Universality tests [μ/e ratios]

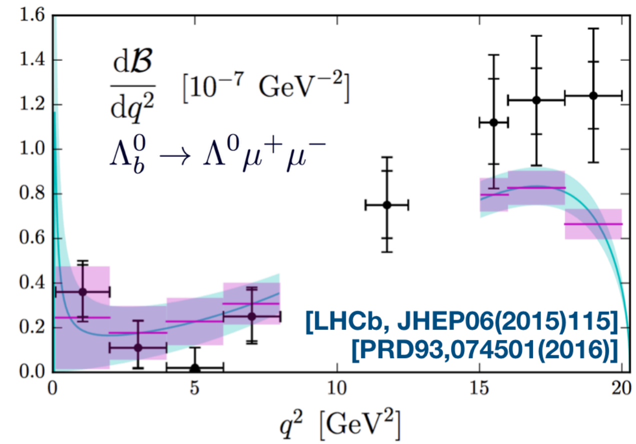


$b \to s \ell^+ \ell^-$ anomalies

Have been observing tensions with the SM prediction for several processes/observables predominantly at low $q^2 = [m(\ell\ell)]^2$

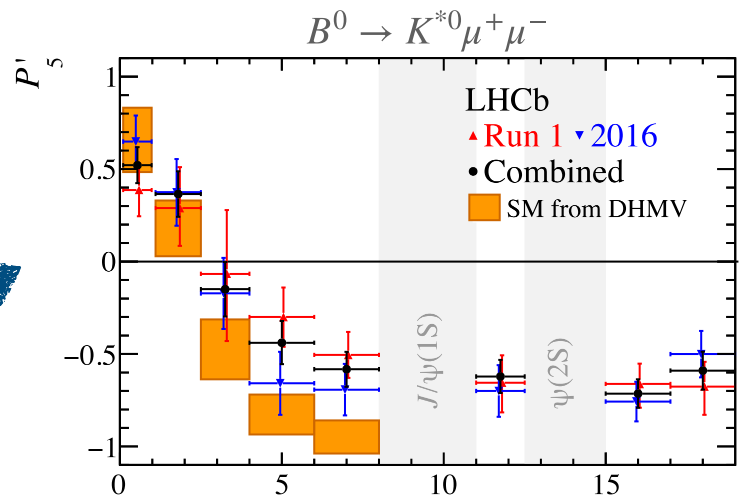




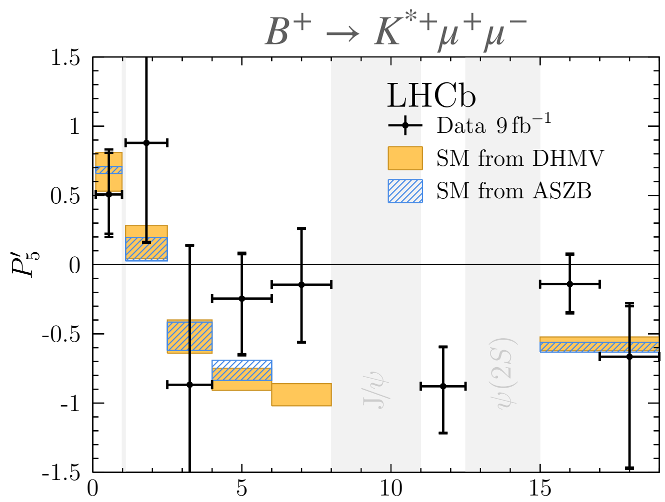


Decay rates

Angular observables



LHCb [PRL 125 (2020) 011802]



LHCb [arXiv:2012.13241]

$b \to s \ell^+ \ell^-$ anomalies

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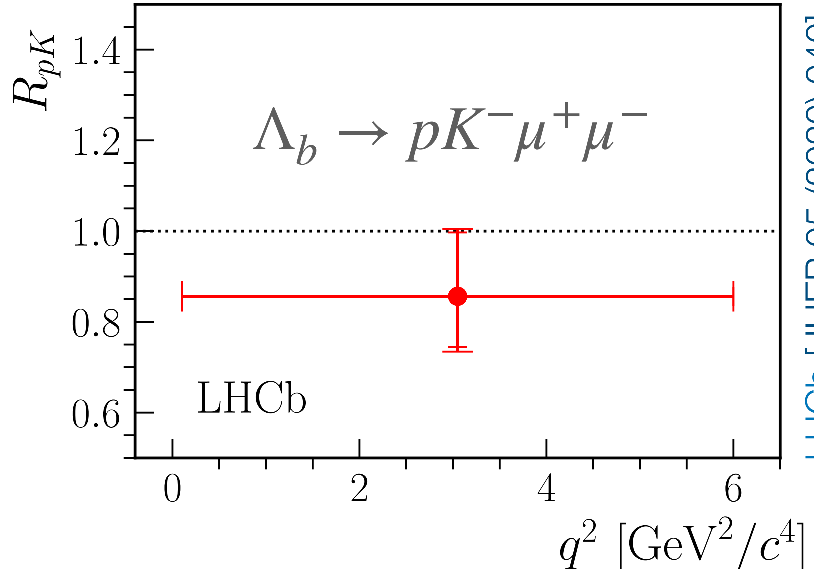
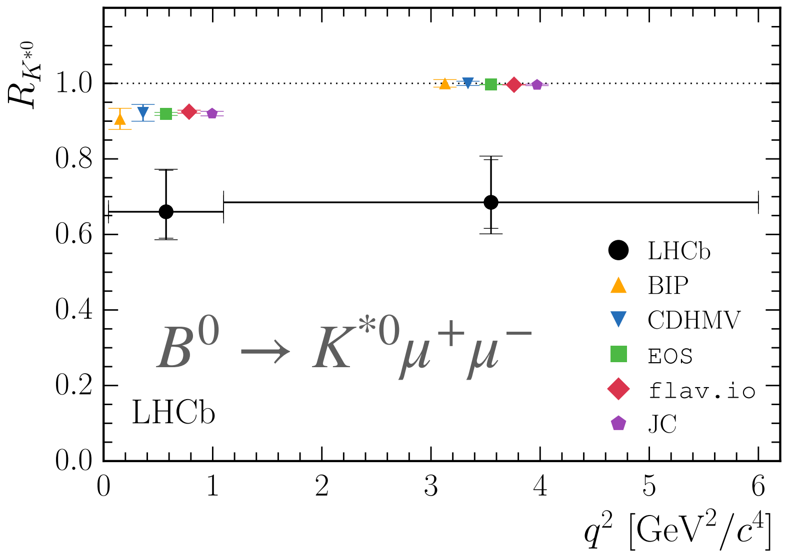
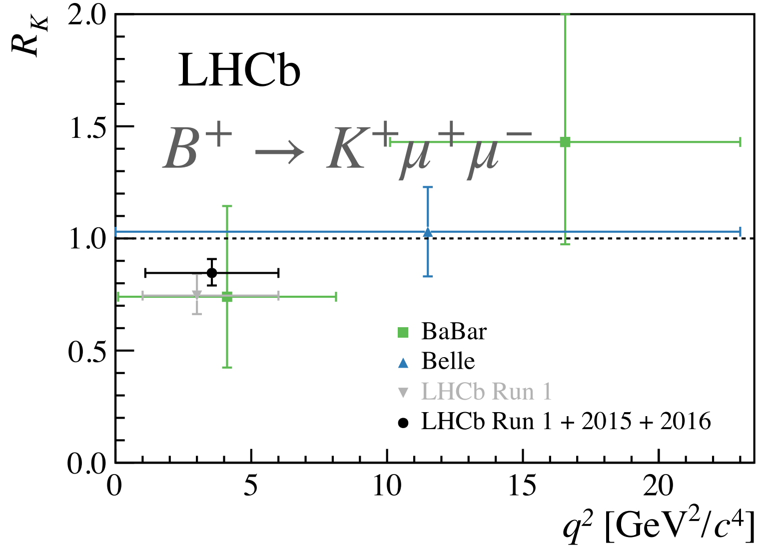
LFU ratios



LHCb [JHEP 05 (2020) 040]



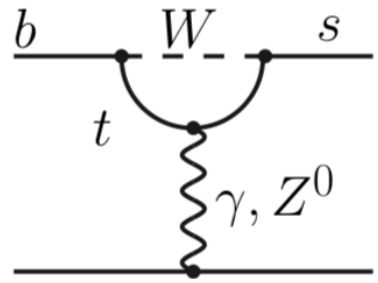
LHCb [JHEP 08 (2017) 055]



BaBar [PRD 86 (2012) 032012]
Belle. [PRL103 (2009) 171801]
LHCb [PRL122 (2019) 191801]

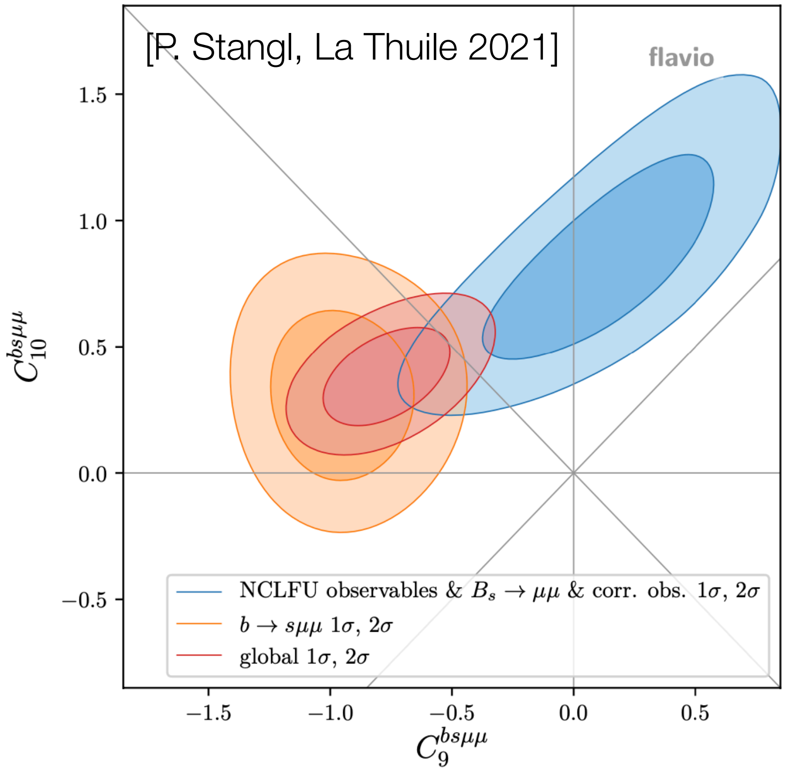
EFT analysis of b→sℓℓ measurements

Describe these interactions in terms of an effective Hamiltonian that describes the full theory at lower energies: $\mathcal{H}_{eff} \sim \sum_i C_i(\mu) O_i(\mu)$



$$\mathcal{O}_9^{(\prime)} = (\bar{s} P_{\mathrm{L(R)}} b)\,(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10}^{(\prime)} = (\bar{s} P_{\mathrm{L(R)}} b)\,(\bar{\ell}\gamma^\mu \gamma^5 \ell)$$



Global fits to b→sℓℓ observables prefer negative shift in C_9 (= $-C_{10}$)

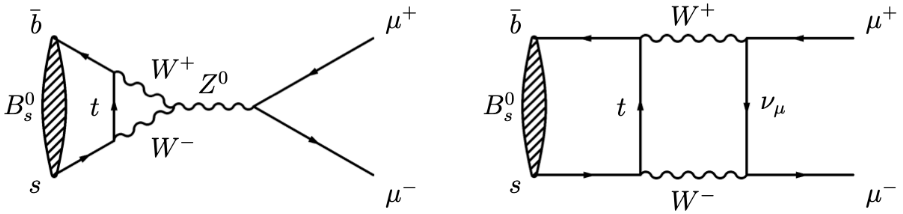
- $B_S \to \mu\mu$ and LFU observables (e.g. $R_{K^{(*)}}$) [theoretically extremely clean]
- Angular observables and branching ratios [underestimated hadronic uncertainties??]

Two new pieces in the puzzle

- New $B^0_{(s)} \to \mu^+\mu^-(\gamma)$ branching ratio & $B^0_s \to \mu^+\mu^-$ effective lifetime
- New Lepton Flavour Universality test in $B^+ \to K^+\ell^+\ell^-$ decays

$B^0_{(S)} \to \mu^+\mu^-$ decays

- FCNC and helicity suppressed



- Extremely precise SM prediction

$$\mathscr{B}(B^0_s \to \mu^+\mu^-)_{\rm SM} = (3.66 \pm 0.14) \times 10^{-9}$$
$$\mathscr{B}(B^0 \to \mu^+\mu^-)_{\rm SM} = (1.03 \pm 0.05) \times 10^{-10}$$

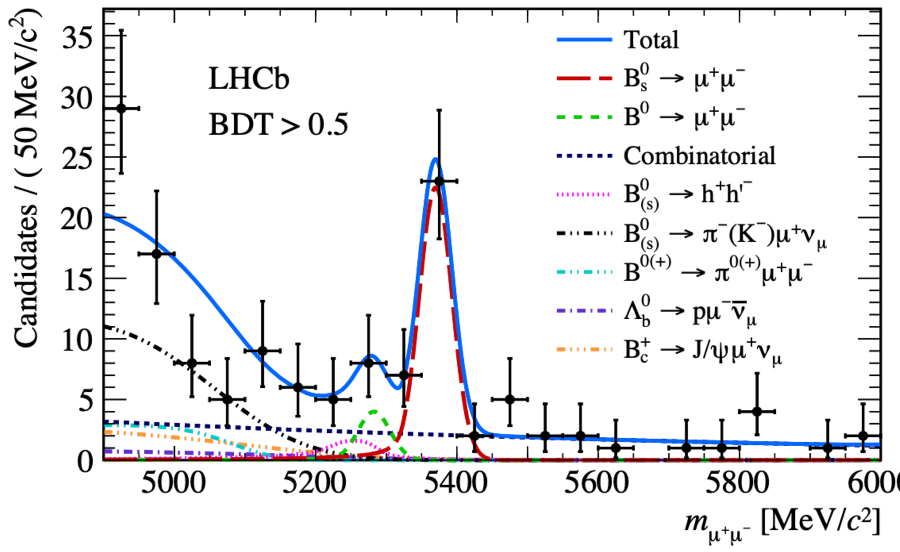
[Beneke et al, JHEP 10 (2019) 232]

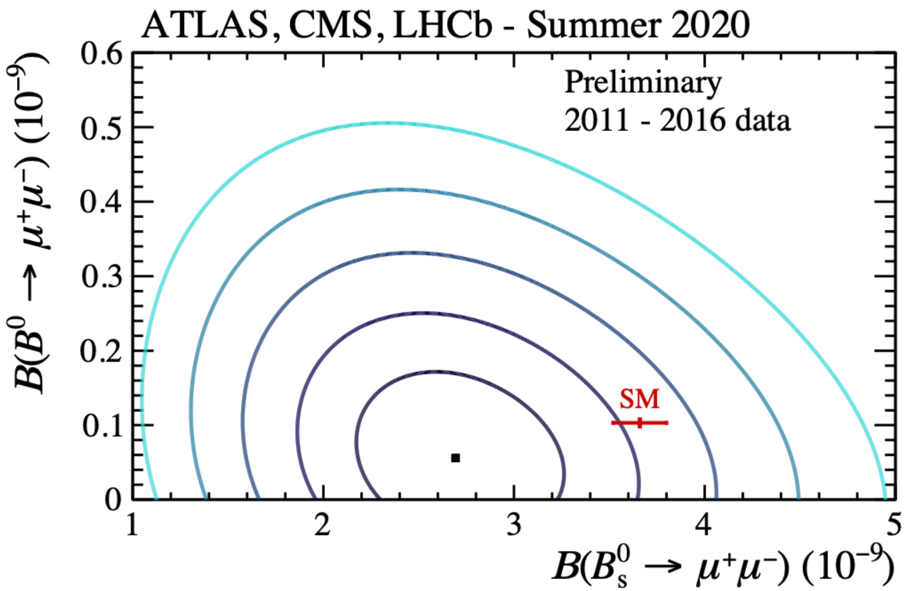
- ATLAS, CMS and LHCb combination

$$\mathscr{B}(B^0_s \to \mu^+\mu^-) = (2.69\ {}^{+0.37}_{-0.35}) \times 10^{-9}$$
$$\mathscr{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10}\ (95\,\%\ \rm CL)$$

Compatible with the SM at 2.1σ

[LHCb, PRL118 (2017) 191801]

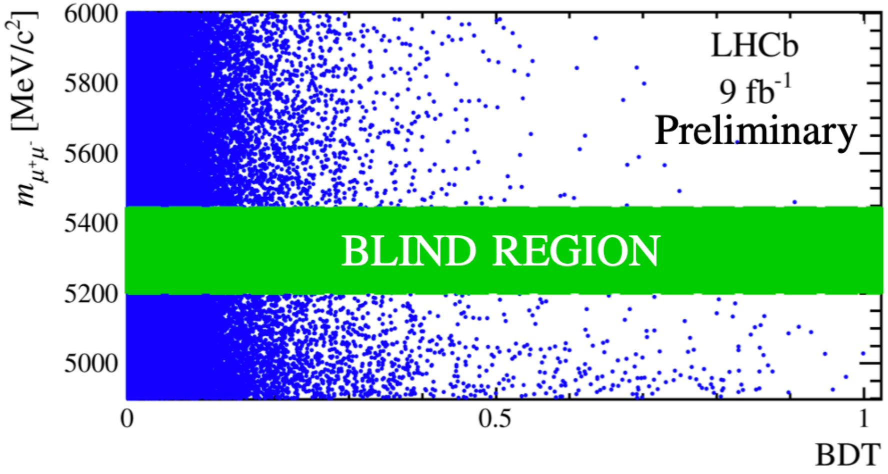


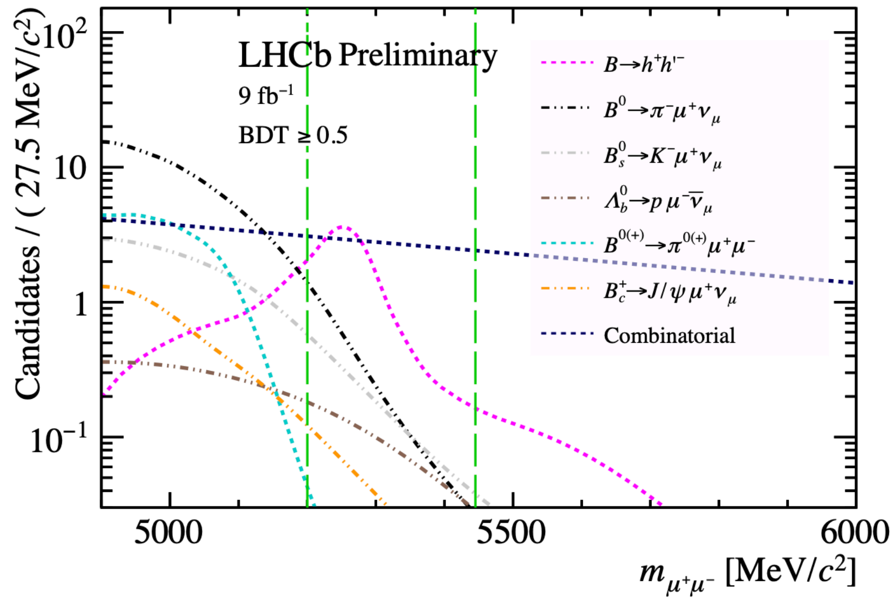


[LHCb-CONF-2020-002, CMS PAS BPH-20-003, ATLAS-CONF-2020-049]

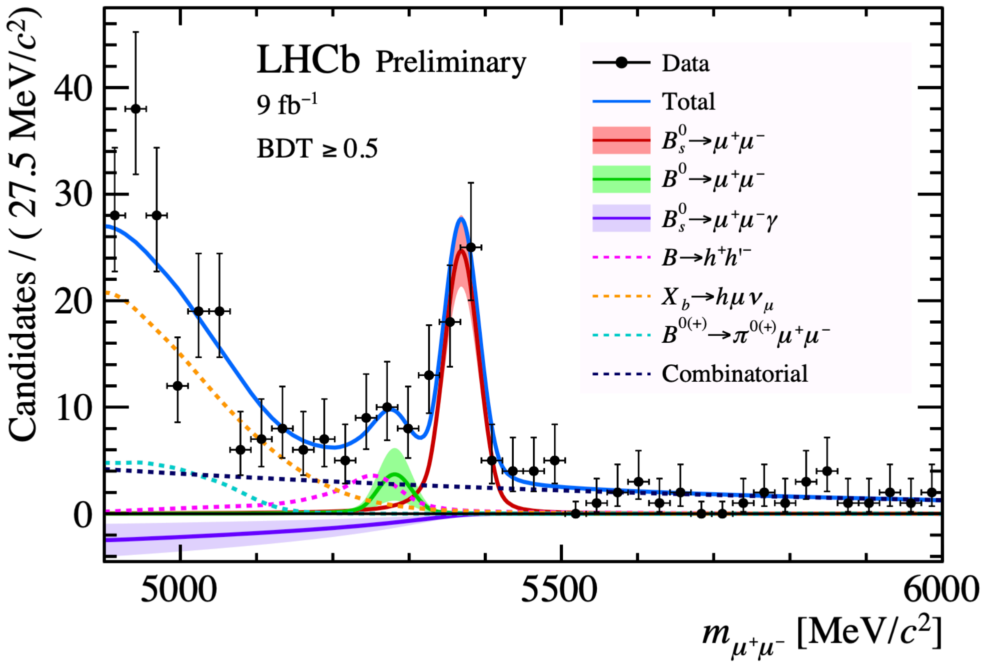
Analysis strategy

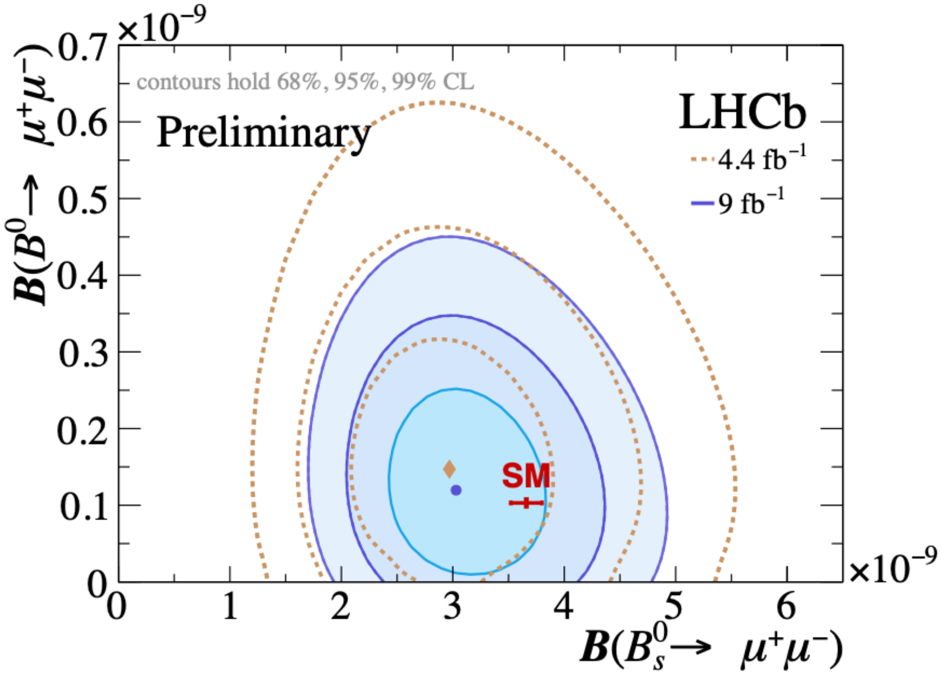
- Update uses full LHCb dataset (Run1+2: 9fb^{-1})
- Dominant background is combinatorial
  - use BDT that exploits isolation and vertex detachment
  - BDT output determined from data-calibrated simulation [crosschecked using $B^0 \to K^+\pi^-$ decays]
- Exclusive backgrounds
  - Semileptonic backgrounds (partially reconstructed)
  - MisID $B^0_{(s)} \to h^+h^-$decays
- Fit m(μμ) simultaneously in 5 bins of BDT
  - Contamination determined from simulation and control channels and constrained in the final fit
- Two normalisations: $B^0 \to K^+\pi^-$ and $B^+ \to J/\psi(\mu\mu)K^+$
  - find excellent agreement between the two





$B^0_{(S)} \to \mu^+\mu^-$ new result





- Find $B_s \to \mu^+\mu^-$ with significance >10σ, but no evidence yet for $B^0 \to \mu^+\mu^-$ (1.7σ)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09\ ^{+0.46}_{-0.43}\ ^{+0.15}_{-0.11}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}\ (95\,\%\,\text{CL})$$

- Set a limit also for the radiative decay (ISR) (1.5σ)

$$\mathcal{B}(B^0 \to \mu^+\mu^-\gamma)_{m_{\mu^+\mu^-}>4.9\text{GeV}} < 2.0 \times 10^{-10}\ (95\,\%\,\text{CL})$$

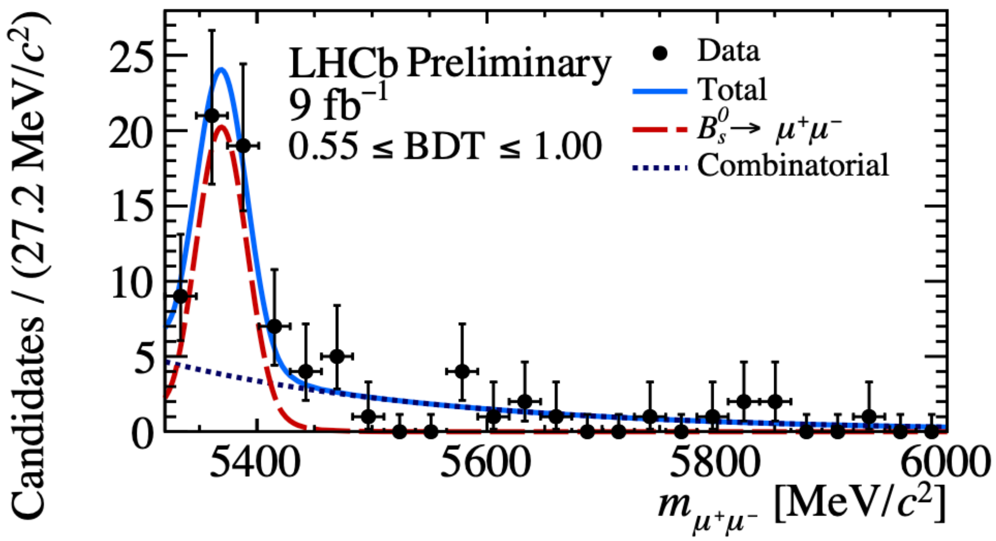
- Main systematics from f_s/f_d (3%), normalisation $\mathcal{B}$ (3%), background description

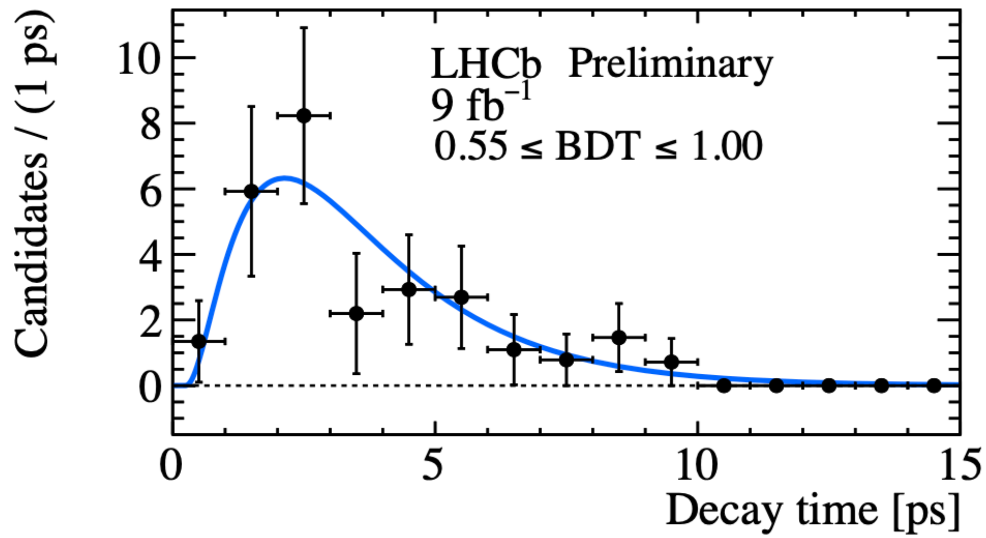
$B^0_s \to \mu^+\mu^-$ effective lifetime

- Clean observable that can offer additional NP constraints
  - In the SM, only CP-odd B_s^0 eigenstate contributes
- Simultaneous fit to background subtracted decay time distribution (sPlot)
  - Use only 2 BDT regions, reduced m(μμ) window
  - Procedure validated by measuring the known $B^0 \to K^+\pi^-$ and $B_s^0 \to K^+K^-$ effective lifetimes

$$\tau_{\mu^+\mu^-} = 2.07 \pm 0.29 \pm 0.03 \text{ ps}$$

Compatible at 1σ (2σ) with CP-odd (CP-even) B_s^0 eigenstate





LFU test in $B \to K\ell^+\ell^-$ decays

- In the SM couplings of gauge bosons to leptons are independent of lepton flavour
  - Branching ratios of e, μ and τ differ only due to lepton mass

$$R_K = \frac{\int \frac{\mathrm{d}\Gamma(B^+ \to K^+\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int \frac{\mathrm{d}\Gamma(B^+ \to K^+e^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2} \stackrel{\mathrm{SM}}{\cong} 1$$

- Very well predicted in the SM ⇒ Any significant deviation is a smoking gun for NP
  - Hadronic contributions cancel in the ratio, uncertainties $O(10^{-4})$ [JHEP 07 (2007) 040]
  - QED corrections can be up to $O(10^{-2})$ [EPJC 76 (2016) 8,440]

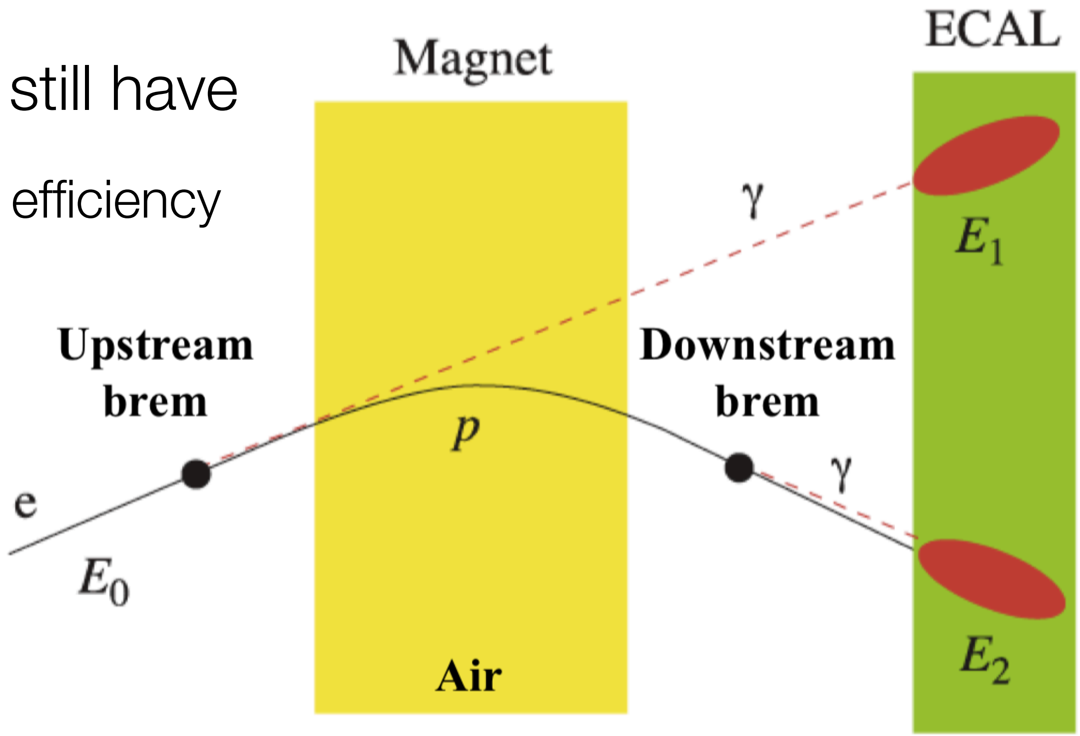
- This update uses the full LHCb dataset, ~twice as many B's as previous analysis (9fb^{-1})

- Follow the same analysis strategy as previous measurement [PRL 122 (2019) 191801]
  - Measurement performed in $1.1 < q^2 < 6.0\ \text{GeV}^2/c^4$

Experimental challenge - electrons vs muons

- Electrons lose a large fraction of their energy through Bremsstrahlung radiation
  - Bremsstrahlung recovery: Look for photon clusters in the calorimeter (ET > 75 MeV) compatible with electron direction before magnet

- After this correction electrons still have
  - Lower reconstruction/trigger/PID efficiency
  - Worse mass and q^2 resolution (more background)



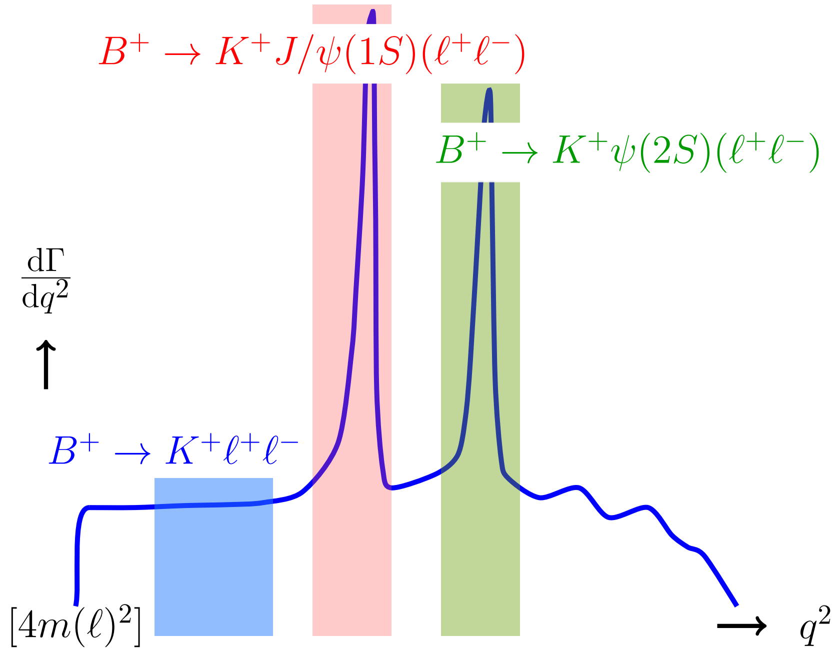
Analysis strategy

- Get differences between muons and electrons fully under control
  - Measurement performed as a double ratio between **rare** and **resonant** modes to cancel most systematics

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))}$$

$$= \frac{N(K^+\mu^+\mu^-)}{N(K^+J/\psi(\mu^+\mu^-))} \cdot \frac{N(K^+J/\psi(e^+e^-))}{N(K^+e^+e^-)}$$

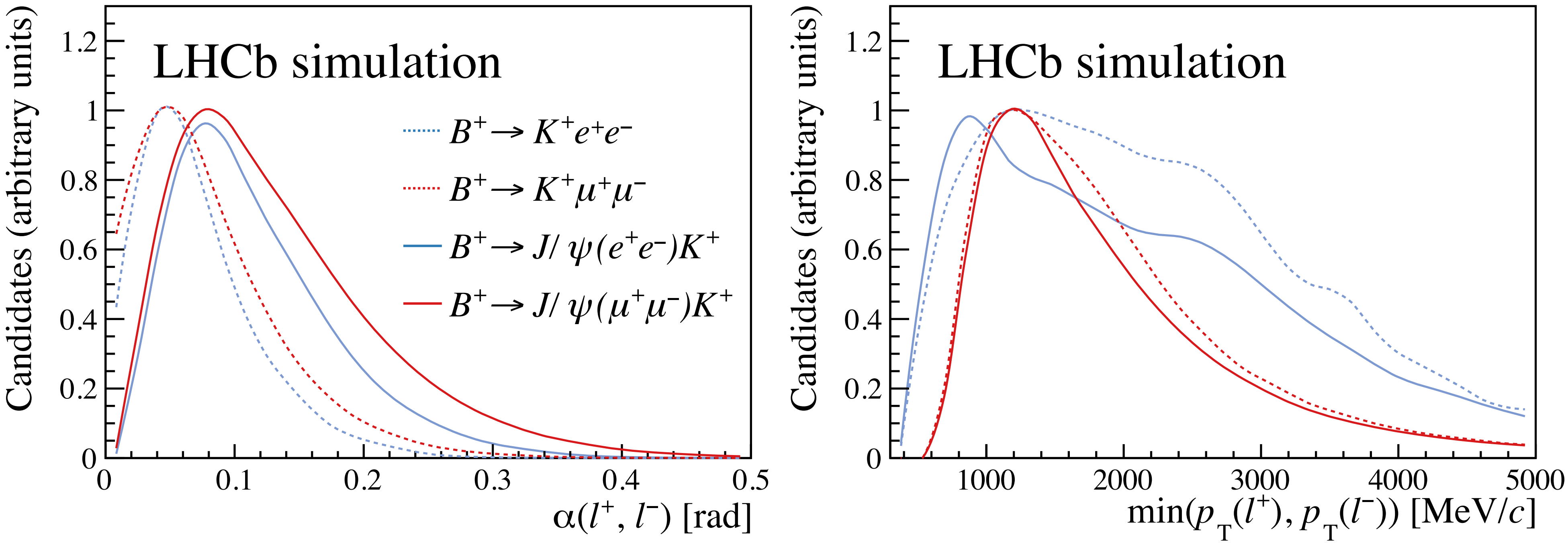
$$\cdot \frac{\varepsilon(K^+J/\psi(\mu^+\mu^-))}{\varepsilon(K^+\mu^+\mu^-)} \cdot \frac{\varepsilon(K^+e^+e^-)}{\varepsilon(K^+J/\psi(e^+e^-))}$$



Two ingredients needed: Efficiencies and yields.

The idea behind the 'double-ratio'

- Large overlap between resonant (——) and rare (····) modes in variables relevant for the detector response (due to the large boost of B's produced at LHCb)



$\Longrightarrow$ Systematic uncertainties cancel to a large extent

Data-driven calibration of the efficiencies

Ratio of efficiencies determined with simulation carefully calibrated using control channels selected from data:

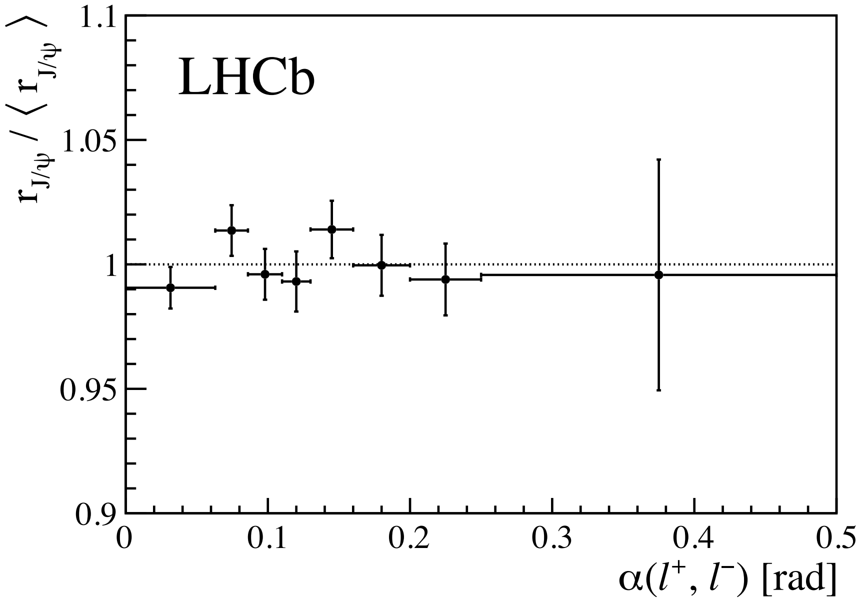
- Particle ID calibration
  - Tune particle ID variables for diff. particle species using kinematically selected calibration samples ($D^{*+} \to D^0(K^-\pi^+)\pi^+$...) [EPJ T&I(2019)6:1]
- Calibration of q^2 and $m(K^+e^+e^-)$ resolutions
  - Use fit to $m(J/\psi)$ to smear q^2 in simulation to match that in data
- B+ kinematics
  - correct simulation to describe kinematics of B's produced at LHCb
- Trigger efficiency
  - Determine trigger efficiency using tag-and-probe method in normalisation modes

Cross-checks

- Checked good understanding of the efficiencies by measuring the single ratio

$$r_{J/\psi} = \frac{B(B^+ \to K^+ J/\psi(\mu^+\mu^-))}{B(B^+ \to K^+ J/\psi(e^+e^-))} = 1$$

$$r_{J/\psi} = 0.981 \pm 0.020 \text{ (stat + syst)}$$



- Under control in all kinematic regions?
  - Measure $r_{J/\psi}$ as a function of kinematic variables

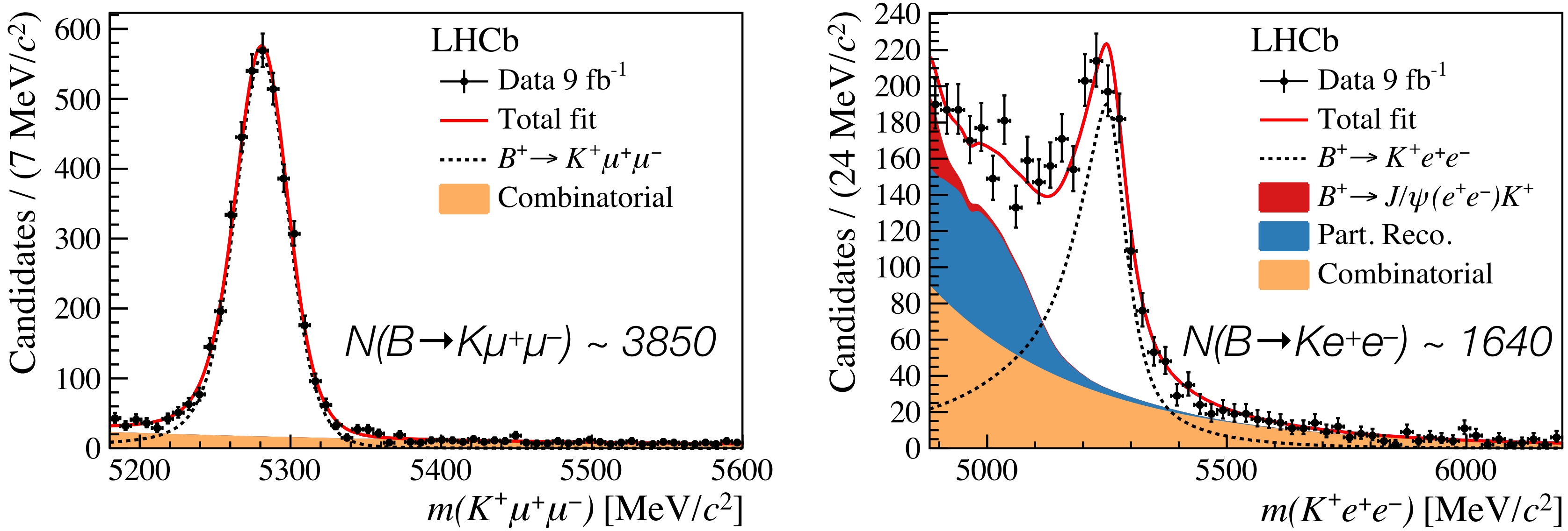
  $\Longrightarrow$ $r_{J/\psi}$ is flat for all variables examined

- Checked also the double ratio in a q^2 region away from the J/ψ

$$R_{\psi(2S)} = \frac{\mathcal{B}(B^+ \to K^+ \psi(2S)(\mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+ \psi(2S)(e^+e^-))}{\mathcal{B}(B^+ \to K^+ J/\psi(e^+e^-))} = 0.997 \pm 0.011 \text{ (stat + syst)}$$

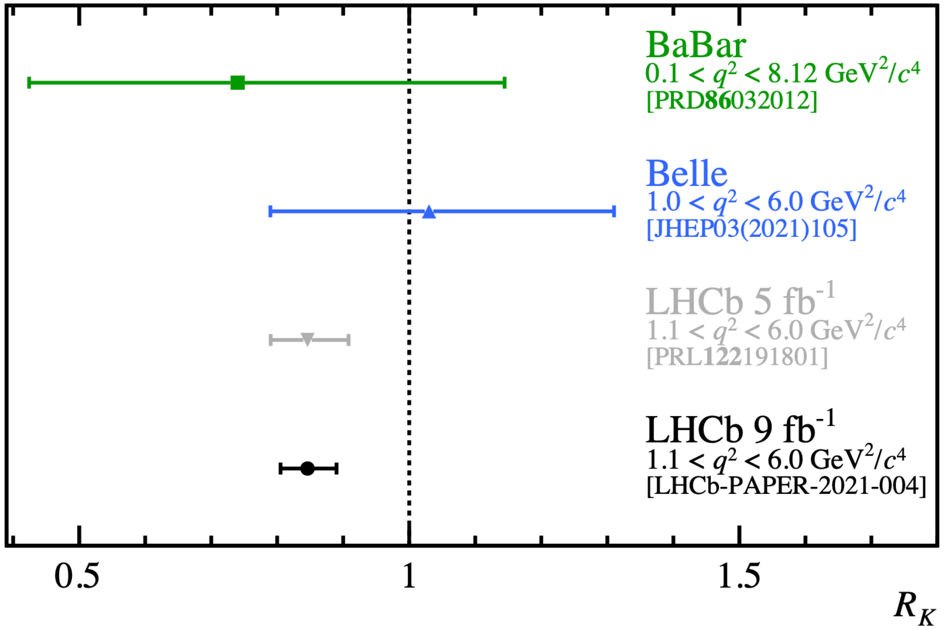
Measurement of R_K

- R_K is extracted from a simultaneous fit to m(Kee) and m(Kμμ) distributions of $B \to K\ell^+\ell^-$ modes



- Correlated uncertainties in efficiency ratios included as multidimensional constraints
- RK still statistically limited, final systematic is small due to good cancellation in double ratio (~1.5%)
  - Uncertainty on the fit models
  - Calibration of efficiencies (statistics of the calibration samples)

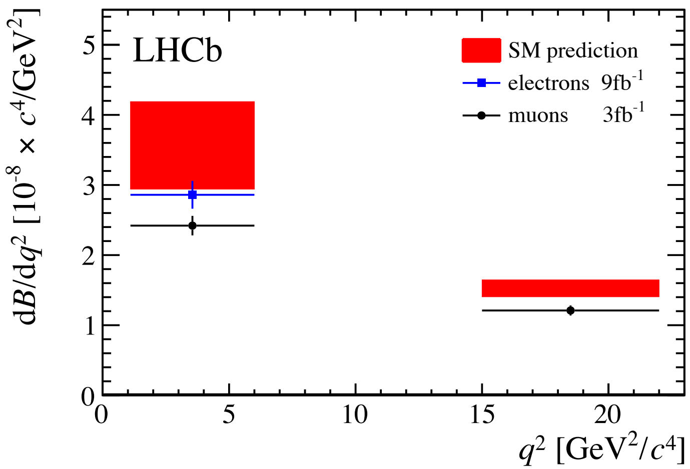
New R_K result



Full Run1 & Run2 result

$$R_K = 0.846 \;^{+0.042}_{-0.039}(\mathrm{stat}) \;^{+0.013}_{-0.012}(\mathrm{syst})$$

Compatible with the SM expectation at **3.1 σ**



Combining this measurement of R_K with

$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ from [LHCb, JHEP 06 (2014) 133]

$$\left.\frac{\mathrm{d}\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathrm{d}q^2}\right|_{1.1<q^2<6.0} = (28.6 \;^{+1.5}_{-1.4}(\mathrm{stat}) \pm 1.4(\mathrm{syst})) \times 10^{-9}\; c^4/\mathrm{GeV}^2$$

Summary & Outlook

- **Processes involving $b \to s\ell^+\ell^-$ transitions are powerful tools to search for NP**

- **Latest results using the full LHCb dataset**
  - Single most precise measurement of $BR(B_S \to \mu\mu)$, most precise measurement of $\tau_{\mu\mu}$ and search of $B_S \to \mu\mu\gamma$ ISR at high m($\mu\mu$)
  - New measurement of R_K, showing the first evidence for LFUV

- **Many results upcoming with the LHCb full Run 2 dataset**
  - updates of R_{K^*}, R_{pK}
  - Measurements of $R\phi$, $R_{K^{*+}}$, R_{KS}, … and high-q2 R_K and R_{K^*}
  - Angular analyses updates, also involving electrons
  - LFV searches and decays involving τ's

- **LHCb upgrade starting on Run3 crucial to consolidate the anomalies, as well as inputs from Belle II and colleagues around the ring**