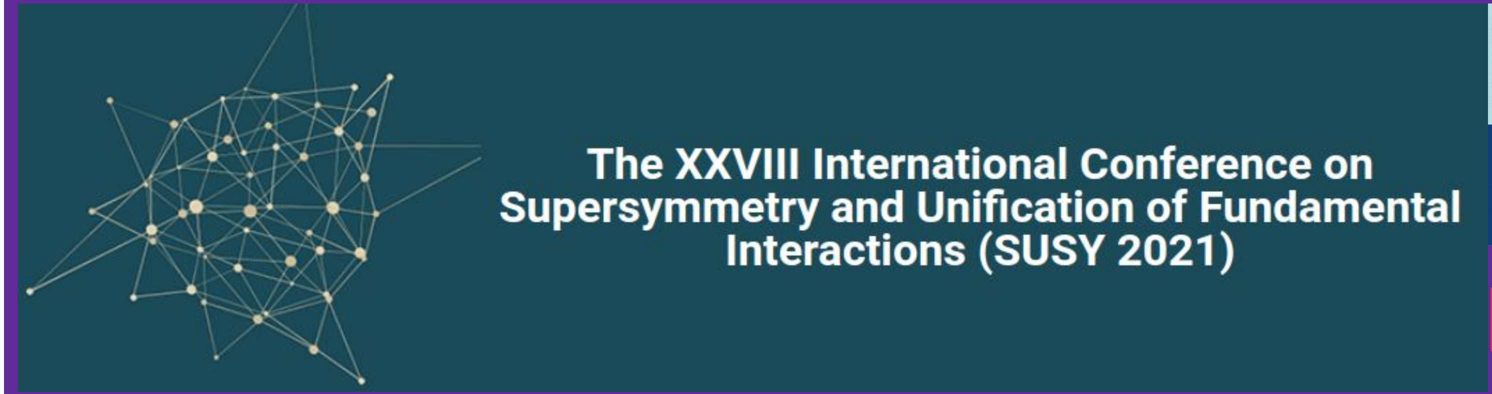
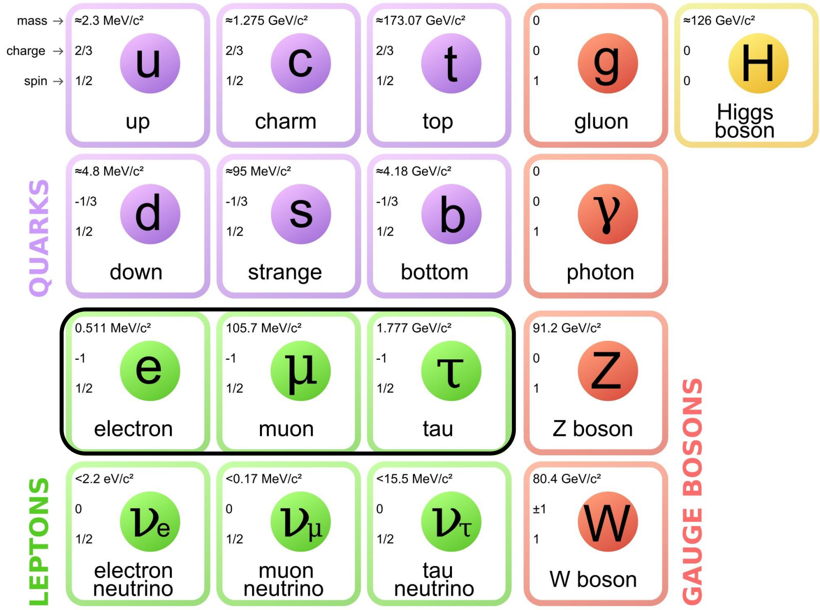
Flavour anomalies at LHCb

Miriam Lucio Martínez, on behalf of the LHCb collaboration



Lepton Flavour Universality



- **In the SM**:
  - **L**epton **F**lavour **U**niversality (**LFU**): electroweak couplings are the same across the three lepton generations
    - Amplitude of processes **identical**, except for phase space and helicity suppression
- **New Physics** explaining the anomalies (*) can be non **LFU**

(*) e.g. [arXiv:2103.16558], [arXiv:2104.08921]

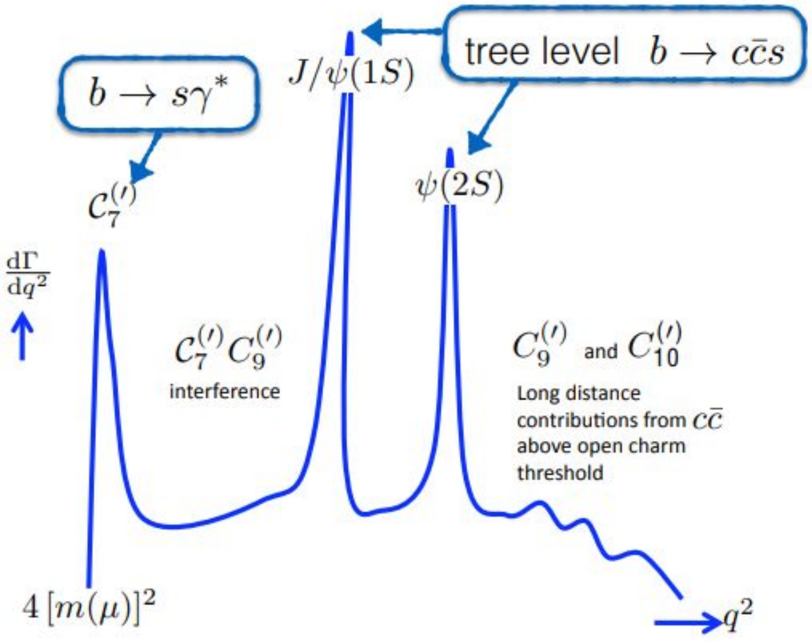
Flavour anomalies in a nutshell

→ $q^2 = m(l^+l^-)^2$

Effective Hamiltonian:

$$\mathcal{H}_{\text{eff}} \propto \sum_i \mathcal{C}_i \mathcal{O}_i$$

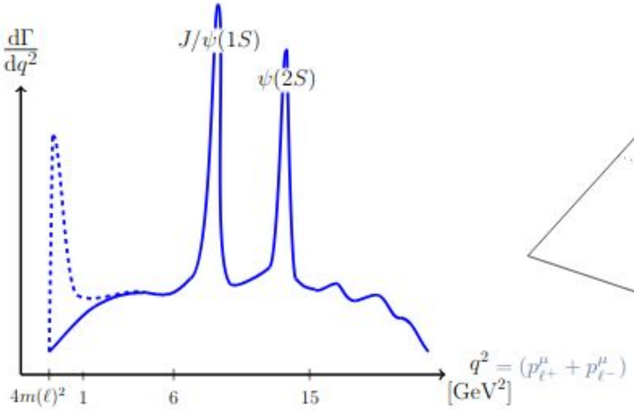
- O_i: local operators
- C_i: Wilson Coefficients
  - New Physics can contribute to different WC depending on its Lorentz structure



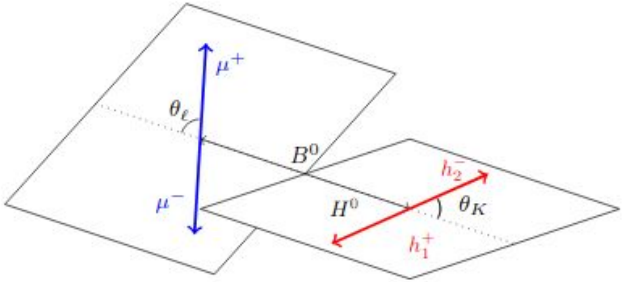
Flavour anomalies in a nutshell

A coherent set of **discrepancies** with respect to the **SM**

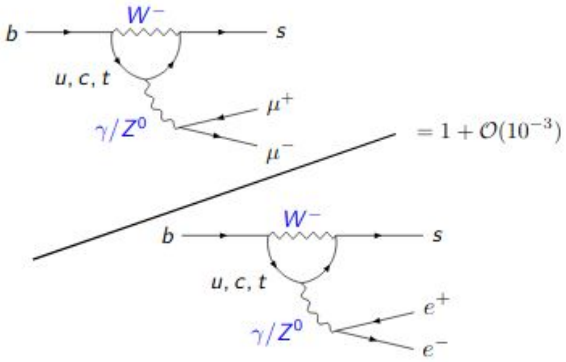
[Branching ratios]



[Angular distributions]



[Lepton Flavour Universality]



High theoretical uncertainties → Low theoretical uncertainties

Today's menu

- R_K [arXiv:2103.11769]
- $B_{(s)}^0 \to \mu^+\mu^- (\gamma)$ [arXiv:2108.09284, arXiv:2108.09283]
- $B^{0(+)} \to K^{*0(+)}\mu^+\mu^-$ [PRL125(2020)011802, PRL126(2021) 161802]
- $B_s^0 \to \varphi\mu^+\mu^-$ [arXiv:2107.13428]
- $\mathcal{B}(B_s^0 \to \varphi\mu^+\mu^-)$ [arXiv:2105.1407]
- $\Lambda_b^0 \to \Lambda\gamma$ [LHCb-PAPER-2021-030, in preparation]

Results including **Run 1 (3 fb^{-1})** and **Run 2 (6 fb^{-1})** data.

R_K [arXiv:2103.11769]

In the **SM:** $$R_X \equiv \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to Xe^+e^-)} \simeq 1$$

- cancellation of hadronic effects
- O(1%) corrections in the central q^2 bin [1.1, 6.0] GeV^2/c^4

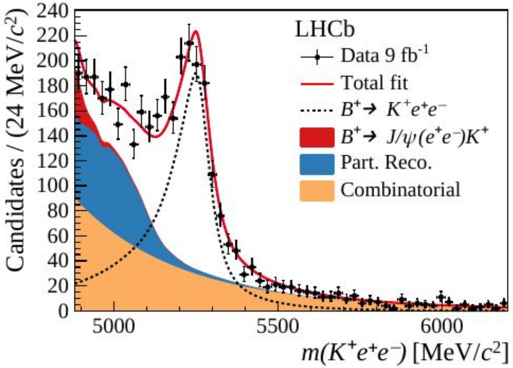
Measure double ratios to better control uncertainties:

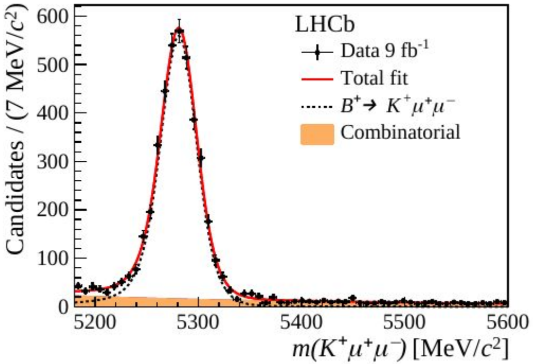
$$R_X \equiv \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to XJ/\psi(\to \mu^+\mu^-))} \frac{\mathcal{B}(B \to XJ/\psi(\to e^+e^-))}{\mathcal{B}(B \to Xe^+e^-)} \simeq 1$$

→ measurement is statistically dominated

Experimental challenges:

1. Electron reconstruction
2. Several background sources
3. Low statistics





R_K [arXiv:2103.11769]

- $B^+ \to K^+ \mathbf{e^+ e^-}$, $B^+ \to K^+ \boldsymbol{\mu^+ \mu^-}$, $\mathcal{B}(B^+ \to K^+ l^+ l^-) \sim 10^{-6}$
- One region of q^2: **central** ($1.1 < q^2 < 6.0$ GeV^2/c^4)
- Analysis performed using the **full Run 1+2 LHCb dataset** (2011 - 2012, 2015 -2018)
- Analysis strategy follows closely the one used in the previous measurement (*)

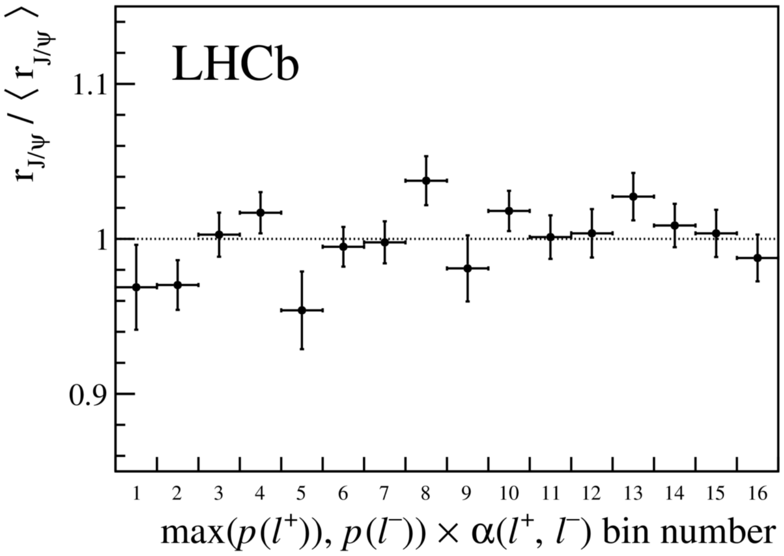
(*) [PRL 122 (2019) 191801]

Unbinned extended maximum-likelihood fit to $m(K^+e^+e^-)$ and $m(K^+\mu^+\mu^-)$:

- Simultaneous across trigger categories and data-taking periods
- Signal yields divided by their corresponding efficiencies to obtain R_K

R_K [arXiv:2103.11769]

- $r_{J/\psi}$ = 0.981 ± 0.021, flat for a number of reconstructed variables (e.g. p_T of B^+)
  - Compatible with unity for all datasets in all trigger samples
- $R_{\psi(2S)}$ = 0.991 ± 0.011, **world-leading test** in ψ(2S) → l^+l^- decays
- Robustness checks across data-taking period, selection category and magnet polarity

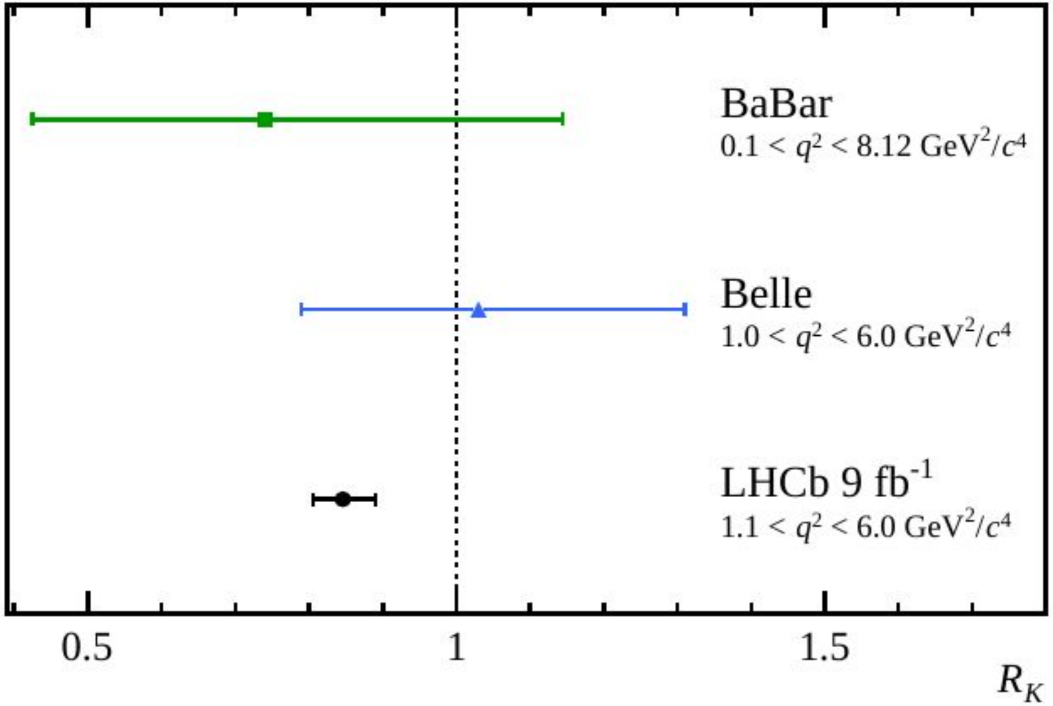


- Using R_K and $\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$ [JHEP 06 (2014) 133]:

$$\frac{d\mathcal{B}(B^+ \to K^+e^+e^-)}{dq^2}(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = (28.6\,^{+1.5}_{-1.4} \pm 1.3) \times 10^{-9}\,c^4/\mathrm{GeV}^2$$

R_K [arXiv:2103.11769]

- **Evidence for breaking of LFU of 3.1σ**

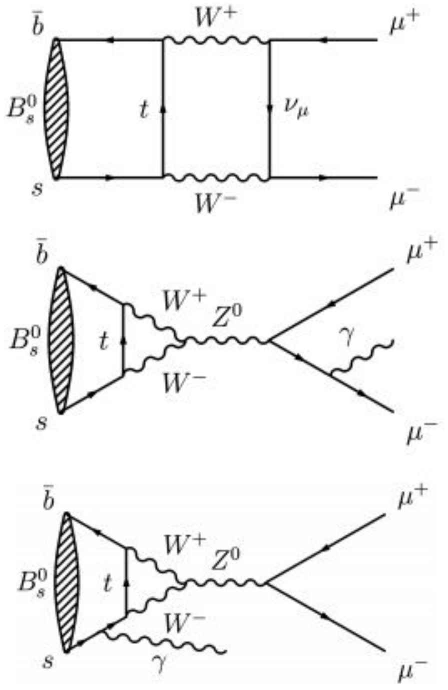


[PRD D86 (2012) 032012]

[JHEP 03 (2021) 105]

$B_{(s)}^0 \to \mu^+\mu^- (\gamma)$ [arXiv:2108.09284, arXiv:2108.09283]

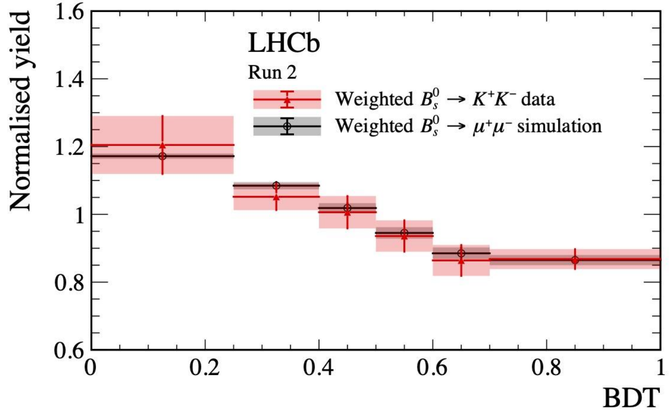
- Very precise SM predictions:
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$, $\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$ [JHEP10 (2019) 232]
- Analysis performed using the **full Run 1+2 LHCb dataset** (2011 - 2012, 2015 -2018)
- **New observable: $\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)$**
  - Initial state radiation measured at low mass
  - High q^2 region, $m_{\mu+\mu-} > 4.9$ GeV/c^2, $\mathcal{B}_{SM}(B_s^0 \to \mu^+\mu^-\gamma) \approx 10^{-10}$ [PRD 97 (2018) 053007]
  - Only experimental limit for B^0 by BaBar [PRD 77 (2008) 011104]
- **Measurement of the effective lifetime of $B_s^0 \to \mu^+\mu^-$, $\tau_{\mu+\mu-}$**
  - Access to the CP structure of the decay
  - In the SM: $\tau_{\mu+\mu-} = 1.62$ ps (CP-odd) vs. 1.42 ps (CP-even, light B_s^0)



$B_{(s)}^0 \to \mu^+\mu^- (\gamma)$ [arXiv:2108.09284, arXiv:2108.09283]

Branching fraction measurement:

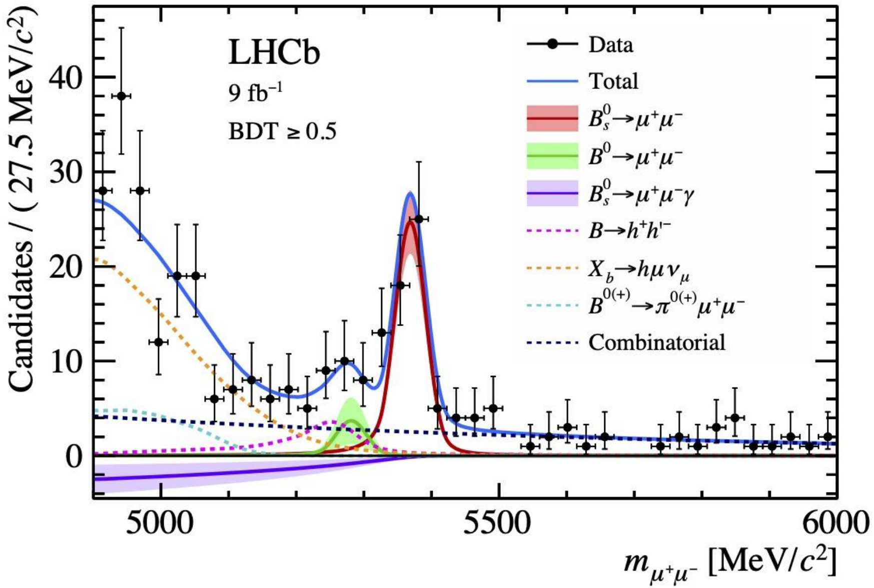
- Selection unchanged with respect to the previous analysis [PRL 118 (2017) 191801] + new BDT calibration
- Separation from signal: $m_{\mu+\mu-}$ and BDT
- Fit done in 5 BDT bins
- Updated values for f_s/f_d, f_u/f_d [arXiv:2103.06810]

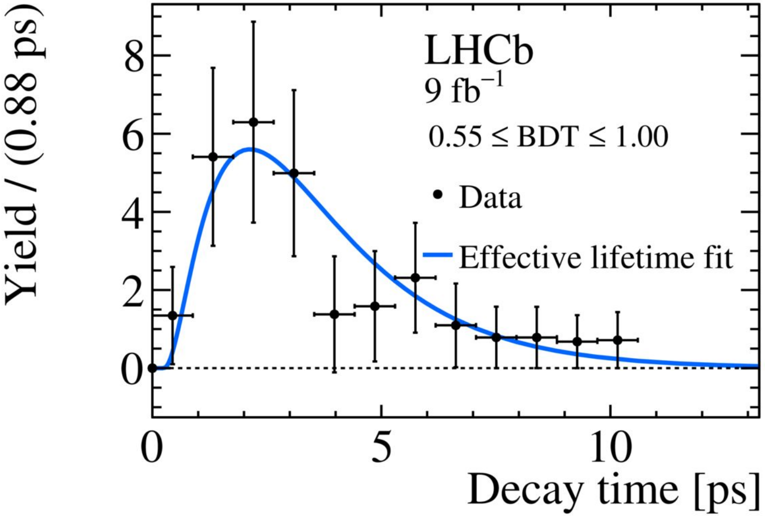


Lifetime measurement:

- Loosen PID requirements with respect to BF measurement
- Fit to background-subtracted data in 2 BDT regions

$B_{(s)}^0 \to \mu^+\mu^-(\gamma)$ [arXiv:2108.09284, arXiv:2108.09283]



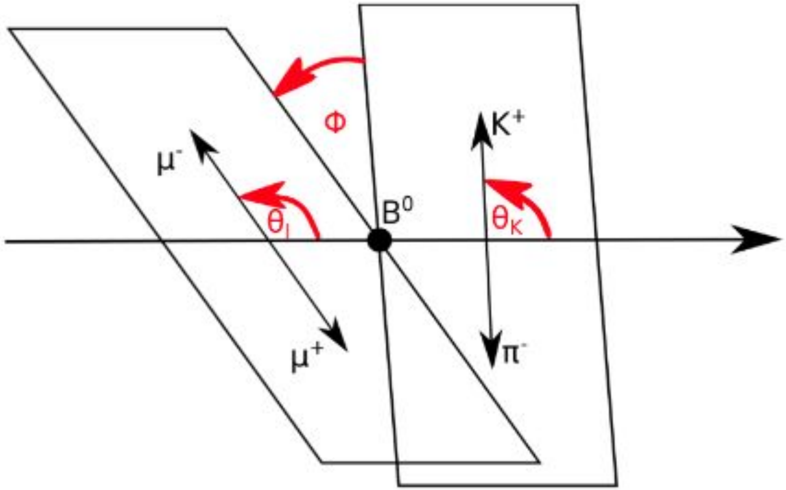


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46}_{-0.43}\,^{+0.15}_{-0.11}\right) \times 10^{-9},$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(1.20\,^{+0.83}_{-0.74} \pm 0.14\right) \times 10^{-10}$$
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma) = (-2.5 \pm 1.4 \pm 0.8) \times 10^{-9}$$
$$\tau_{\mu^+\mu^-} = 2.07 \pm 0.29 \pm 0.03\,\text{ps}$$

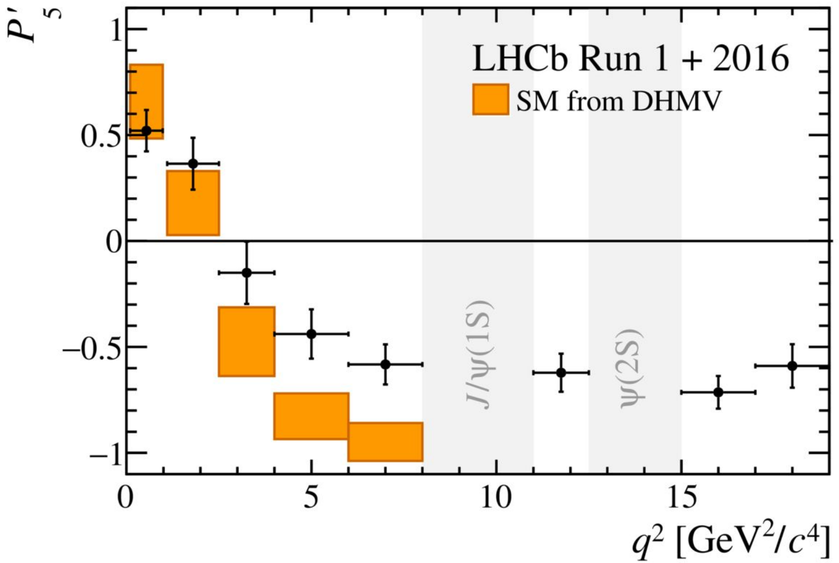
$\tau_{\mu+\mu-}$ compatible at 1σ (2σ) with CP-odd (CP-even) SM eigenstates

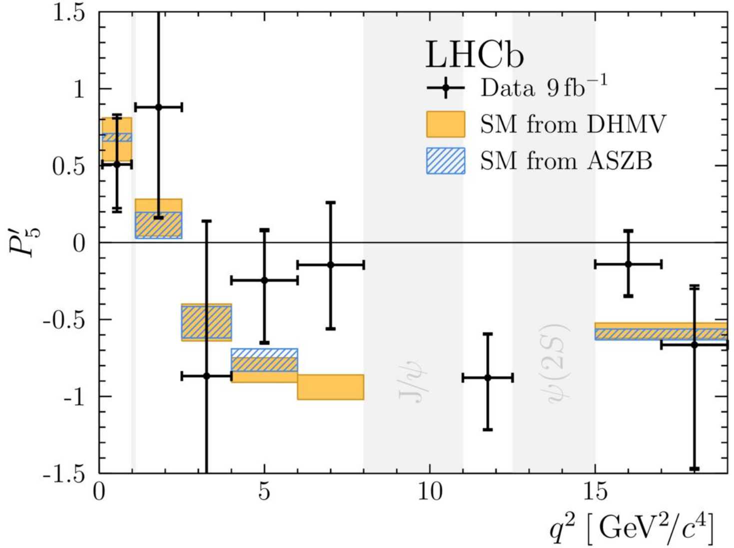
$B^{0(+)} \longrightarrow K^{*0(+)}\mu^+\mu^-$ [PRL 125 (2020) 011802, PRL 126 (2021) 161802]

- $B^0 \rightarrow K^{*0} (\rightarrow K^+\pi^-) \mu^+\mu^-$, $B^+ \rightarrow K^{*+} (\rightarrow K_S^0\pi^+) \mu^+\mu^-$ **described** by 3 helicity angles + q^2
- Analyses performed using the **Run 1+ 2016 (B^0) and full Run 1 + Run 2 (B^+) LHCb dataset**
- Optimised set of observables that cancel form-factor uncertainties [JHEP 01 (2013) 048]
- Contamination from S-wave configuration in $m(K^+\pi^-)/m(K_S^0\pi^+)$ taken into account



$B^{0(+)} \to K^{*0(+)}\mu^+\mu^-$ [PRL125(2020)011802, PRL126(2021) 161802]





- Overall tension with SM is observed to increase mildly
- Pattern of deviations from SM broadly agrees with $B^0 \to K^{*0}\mu^+\mu^-$

$B_s^0 \to \phi\mu^+\mu^-$ [arXiv:2107.13428]

- Analysis performed with **Run 1 and 2016-2018 LHCb dataset**
- $B_s^0 \to \Phi(\to K^+K^-)\,\mu^+\mu^-$ fully described with q^2 + helicity angles + decay time of B_s^0
- **Untagged decays:**
  - Presence of CP asymmetries (~ 0 in the SM) as well as CP averages
  - P_5' cannot be accessed in this analysis

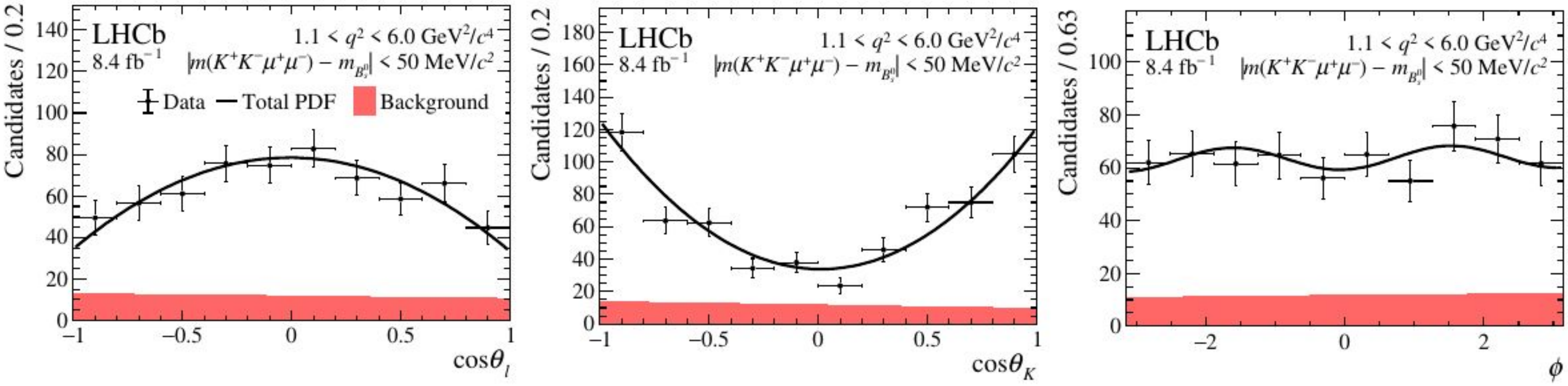
Unbinned maximum likelihood fit to $m(K^+K^-\mu^+\mu^-)$ and helicity angles:

1. $q^2 < 12.5$ GeV^2/c^4: ~2 GeV^2/c^4 wide q^2 regions + $1.1 < q^2 < 6.0$ GeV^2/c^4
2. $q^2 > 15.0$ GeV^2/c^4: $15.0 < q^2 < 18.9$ GeV^2/c^4

→ maximise sensitivity to potential short-distance NP contributions and keep fit stable

$B_s^0 \to \phi\mu^+\mu^-$ [arXiv:2107.13428]

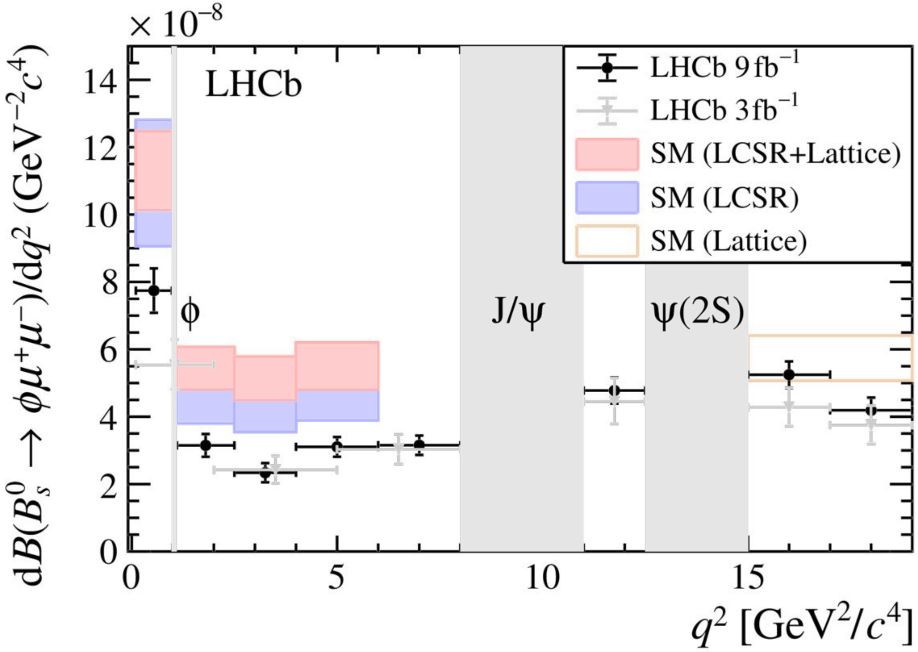
- Overall good agreement with SM, CP asymmetries compatible with 0
- Two-fold increase in sensitivity compared to previous results [JHEP 09 (2015) 79]



$\mathcal{B}(B_s^0 \rightarrow \phi\mu^+\mu^-)$ [arXiv:2105.1407]

- Analysis performed using the **full Run 1+2 LHCb dataset** (2011 - 2012, 2015 -2018)
  - Different efficiencies → split in 2011-2012, 2015-2016, 2017-2018 periods
- $\mathcal{B}(B_s^0 \rightarrow \Phi(\rightarrow K^+K^-)\mu^+\mu^-)$: simultaneous extended maximum-likelihood fit:
  - In intervals of q^2
  - S-wave configuration in K^+K^- considered negligible
- $\mathcal{B}(B_s^0 \rightarrow f_2'(1525)(\rightarrow K^+K^-)\mu^+\mu^-)$: simultaneous fit in the combined q^2 region [0.1, 0.98] + [1.1, 8.0] + [11.0, 12.5] GeV^2/c^4
  - 2D fit to $m(\mu^+\mu^-K^+K^-)$ and $m(K^+K^-)$ to separate S-wave from P-wave configurations

$\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)$ [arXiv:2105.1407]



$\mathcal{B}(B_s^0 \to f_2'(\to K^+K^-)\mu^+\mu^-)$

$$\mathcal{B}(B_s^0 \to f_2'\mu^+\mu^-) = (1.57 \pm 0.19 \pm 0.06 \pm 0.06 \pm 0.08) \times 10^{-7}$$

- First **observation** of a rare semileptonic decay involving a spin-2 meson in the final state
- Value for the BF in agreement with SM

$\mathcal{B}(B_s^0 \to \Phi(\to K^+K^-)\mu^+\mu^-)$

- 3.6σ deviation from SM for $1.1 < q^2 < 6.0$ GeV^2/c^4
- Using combination of Light Sum Cone Rule and Lattice QCD calculations

$\Lambda_b^0 \rightarrow \Lambda\gamma$ [LHCb-PAPER-2021-030, in preparation]

- Photons emitted in *b* decays are predominantly **left-handed** in the SM ⇒ right-handed polarization is a clear hint of **BSM physics**
- Radiative decays of *b* baryons: direct measurement of the **photon polarization (α_γ)**
  - Λ helicity measurement in $\Lambda_b^0 \rightarrow \Lambda\gamma$
- Additional measurement of **CP angular asymmetries**, < O(1%) in the SM
- $\Lambda_b^0 \rightarrow \Lambda (\rightarrow p\pi^-)\gamma$ reconstructed using **full Run 2 dataset**

Photon polarization measurement:

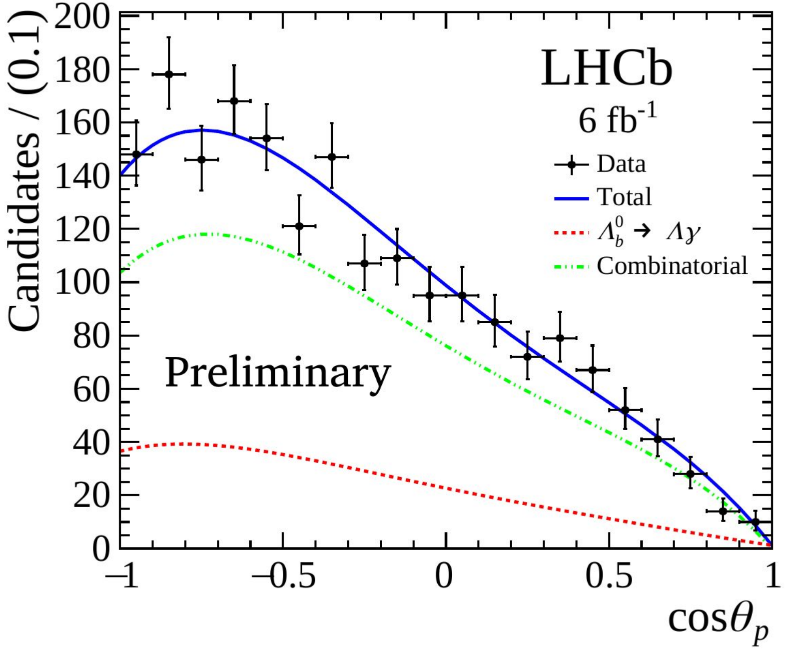
- Maximum likelihood fit to $m(p\pi^-\gamma)$ to disentangle signal from background
- Unbinned maximum likelihood fit to $\cos(\theta_p)$ to obtain the **photon polarization**
  - θ_p: angle between p_p in the Λ rest frame and p_Λ in the Λ_b^0 rest frame

$\Lambda_b^0 \rightarrow \Lambda\gamma$ [LHCb-PAPER-2021-030, in preparation]

- **CP asymmetry:** separate sample into $\Lambda_b^0 \rightarrow \Lambda\gamma$ and its CP conjugate and measure the photon polarization in each case

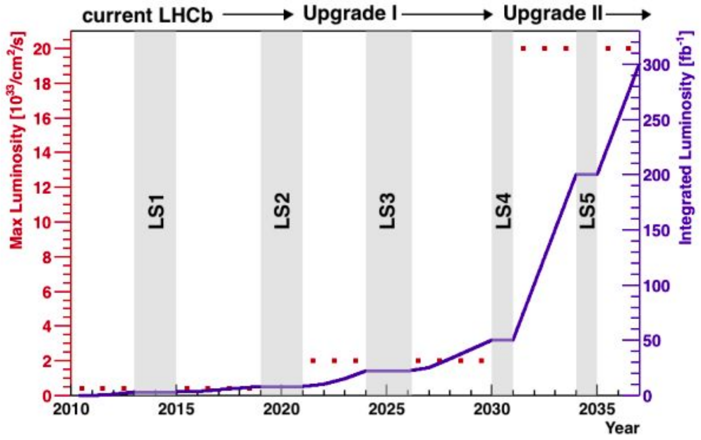
$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\,(\text{stat.})^{+0.04}_{-0.13}\,(\text{syst.})$$

- Compatible with the SM
- Results consistent with no CP asymmetry
- Both results are **first time measurements**

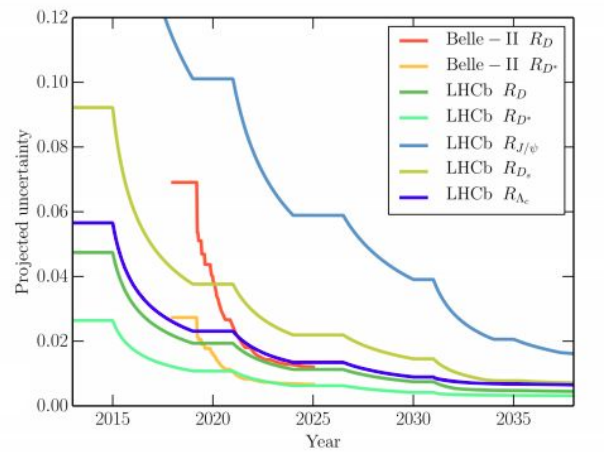


A word about the future @ LHCb

- Run 2 updates + new measurements: $R(D_s^*)$, $R(\Lambda_c)$, $R(K\pi\pi)$, $R(K^{*+})$, $R(K_S^0)$, $B_s^0 \to \phi\tau\mu$, $\Lambda^0_b \to \Lambda e^{\pm}\mu^{\mp}$, form factors … in the pipeline
- In the **Upgrade I (2021 - 2030)**, LHCb will collect ~50 fb^{-1}, 5x luminosity in Run 1 and Run2 combined (9fb^{-1})



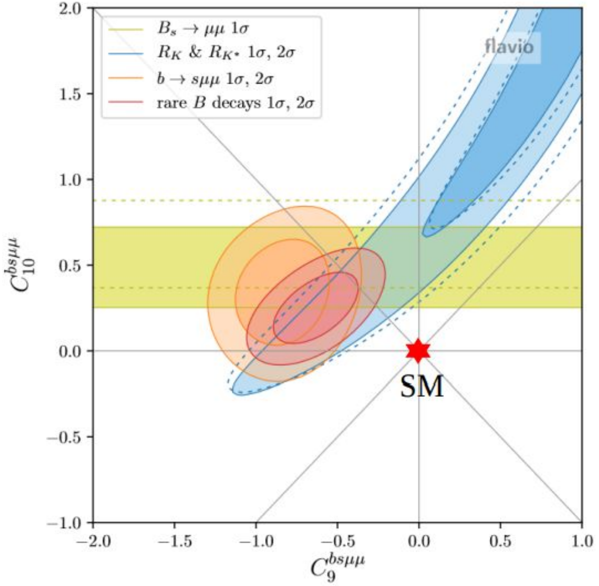
[arXiv:1808.08865]



[J. Phys. G: Nucl. Part. Phys. 46 (2019) 023001]

Conclusions

- An intriguing set of anomalies has been measured by LHCb, BaBar and Belle
  - Angular analyses, branching fraction measurements and Lepton Flavour Universality tests constitute good probes for New Physics
- Presented the latest set of measurements from LHCb
- We need more statistics to understand and disentangle possible New Physics contributions
- More results to come + measurements from **Belle II** and the **LHCb Upgrade** will help to further clarify the situation



[arXiv:2103.13370]

STAY TUNED!

Thanks for your attention!

Angular decay rate

$$\left.\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}}\right|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

$B^0 \to K^{*0}e^+e^-$ [JHEP 12 (2020) 081]

- Low q^2 range to isolate $b \to se^+e^-$ transitions dominated by the **$b \to s\gamma$** contribution
  - Photons emitted are predominantly left-handed in the SM
  - Unique information related to the $C_7^{(\prime)}$ Wilson Coefficients
- Analysis performed with **full Run 1 and Run 2 LHCb dataset**
- $B^0 \to K^{*0} (\to K^+\pi^-) e^{+-}$ **fully described** by 3 helicity angles + q^2
  - Transformation $\Phi = \Phi + \pi$ if $\Phi < 0$ simplifies the PDF
  - S-wave contribution is neglected

Observables:

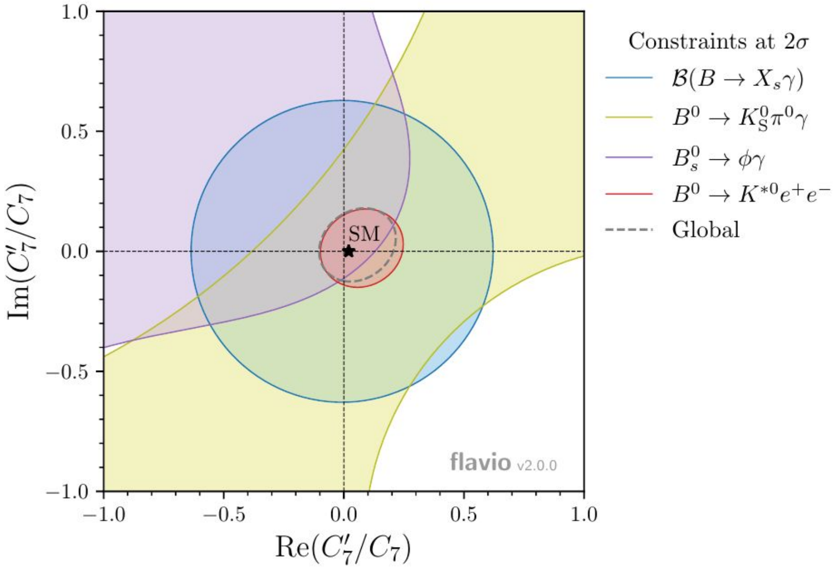
- F_L: longitudinal polarisation fraction of the K^{*0} meson (expected small)
- A_T^{Re}: related to forward-backward asymmetry $A_T^{Re} = 4A_{FB}(1\text{-}F_L)/3$
- $A_T^{(2)}$ and A_T^{Im}: transverse asymmetries, closely related to the **photon polarisation** in $B0 \to K^{*0}\gamma$

$B^0 \to K^{*0}e^+e^-$ [JHEP 12 (2020) 081]

- $0.0008 < q^2 < 0.257$ GeV^2/c^4 to prevent degradation in the angular resolution
- Bremsstrahlung radiation corrected for [JHEP 08 (2017) 055]
- 4D fit to the angular distributions and $m(K^+\pi^-e^+e^-)$:
  - Dataset divided into two trigger categories
  - Run 1 and Run 2 data treated separately

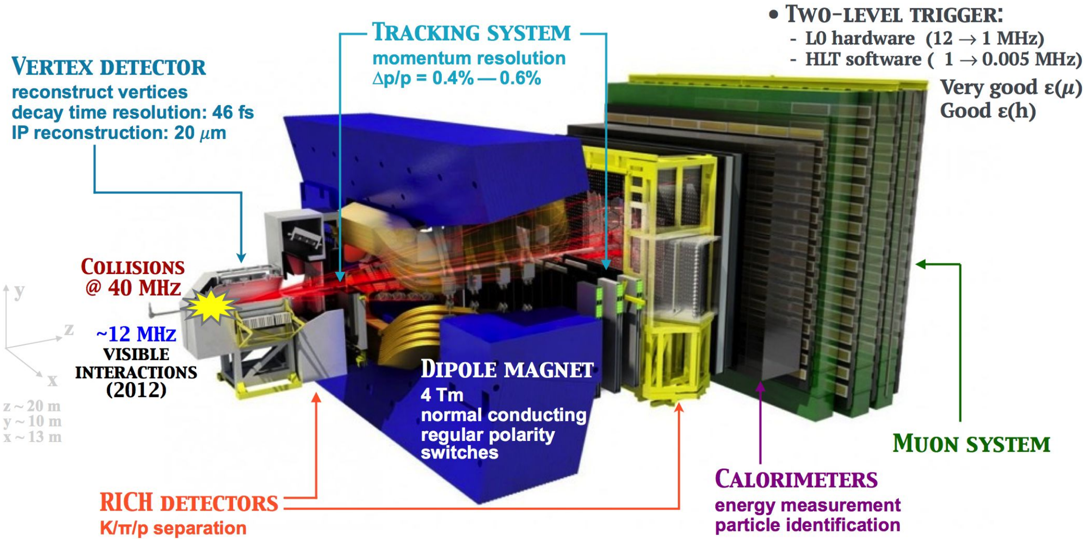
$$
\begin{aligned}
F_{\mathrm{L}} &= 0.044 \pm 0.026 \pm 0.014 \\
A_{\mathrm{T}}^{\mathrm{Re}} &= -0.06 \pm 0.08 \pm 0.02 \\
A_{\mathrm{T}}^{(2)} &= +0.11 \pm 0.10 \pm 0.02 \\
A_{\mathrm{T}}^{\mathrm{Im}} &= +0.02 \pm 0.10 \pm 0.01
\end{aligned}
$$

Consistent with SM predictions.



The LHCb detector

Single forward-arm spectrometer



- Acceptance down to low p_T
- Particle ID
- Momentum & mass reconstruction
- Vertexing
- Trigger for hadronic and leptonic modes
- Can operate in pp, pPb, PbPb and fixed-target

R(D*) muonic

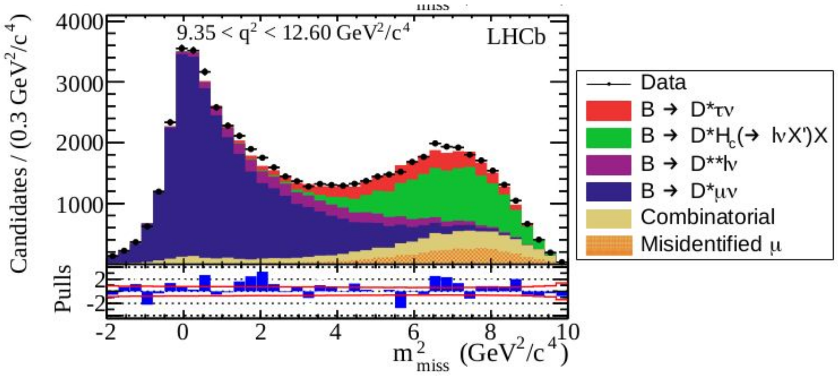
[PRL 115, (2015) no.11, 111803]

$$R_{D^*} \equiv \frac{\mathcal{B}(B \to D^* \tau \nu_\tau)}{\mathcal{B}(B \to D^* \mu \nu_\mu)} = 0.258 \pm 0.005$$ [HFLAV average]

- Fit using a maximum likelihood method with 3D templates representing signal + background + **normalization** ($B^0 \to D^{*-} \mu^+ \nu_\mu$)
  - In bins of m^2_{miss}, E^*_μ and q^2
- MVA techniques based on μ isolation used to suppress large backgrounds from **partially reconstructed B-decays**

$$\mathcal{R}(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$$

➢ ~1.9σ **above** the SM value



R(J/ψ) muonic

[PRL 120 (2018) 121801]

$$R(J/\psi) = \frac{B_c^+ \to J/\psi \tau^+ \nu_\tau}{B_c^+ \to J/\psi \mu^+ \nu_\mu} \in [0.25, 0.28] (\mathrm{SM})$$

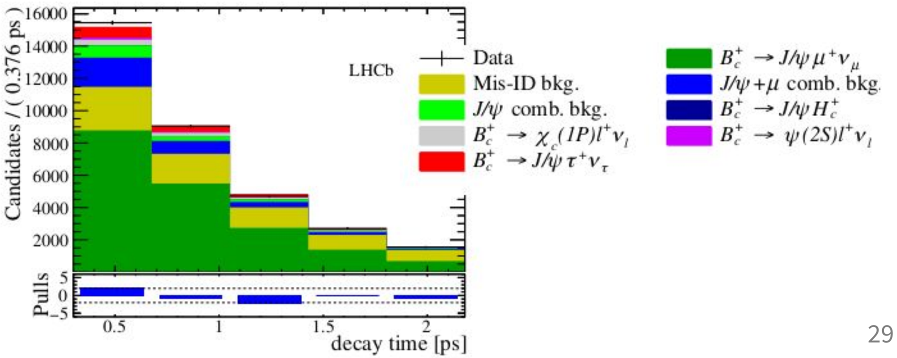
[PLB 452 (1999) 129] [arXiv:hep-ph/0211021] [PRD 73 (2006) 054024] [PRD 74 (2006) 074008]

- Run 1 analysis, using $B^+_c \to J/\psi\mu^+\nu_\mu$ as **normalization** mode, with $J/\psi \to \mu^+\mu^-$
- Multidimensional **fit** to the data using templates:
  - Largest background component is misID (templated using data-driven approach)

$$R(J/\psi) = 0.71 \pm 0.17(\mathrm{stat}) \pm 0.18(\mathrm{syst})$$

➢ Within 2σ from the SM

➢ Largest systematic from form factors

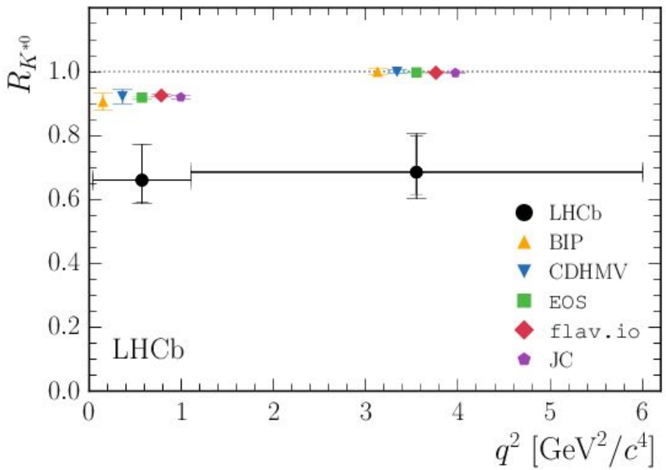


R(K*)

[JHEP 1708 (2017) 055]

- $X = K^* \Longrightarrow B \to K^*e^+e^-$, $B \to K^*\mu^+\mu^-$
- Two regions of q^2: low and central
- Run 1 data (2011 - 2012)
- Similar cross-checks as for R(K)

$$R_{K^{*0}} = \begin{cases} 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}) \text{ for } 0.045 < q^2 < 1.1\text{GeV}^2/c^4 \\ 0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst}) \text{ for } 1.1 < q^2 < 6.0\text{GeV}^2/c^4 \end{cases}$$

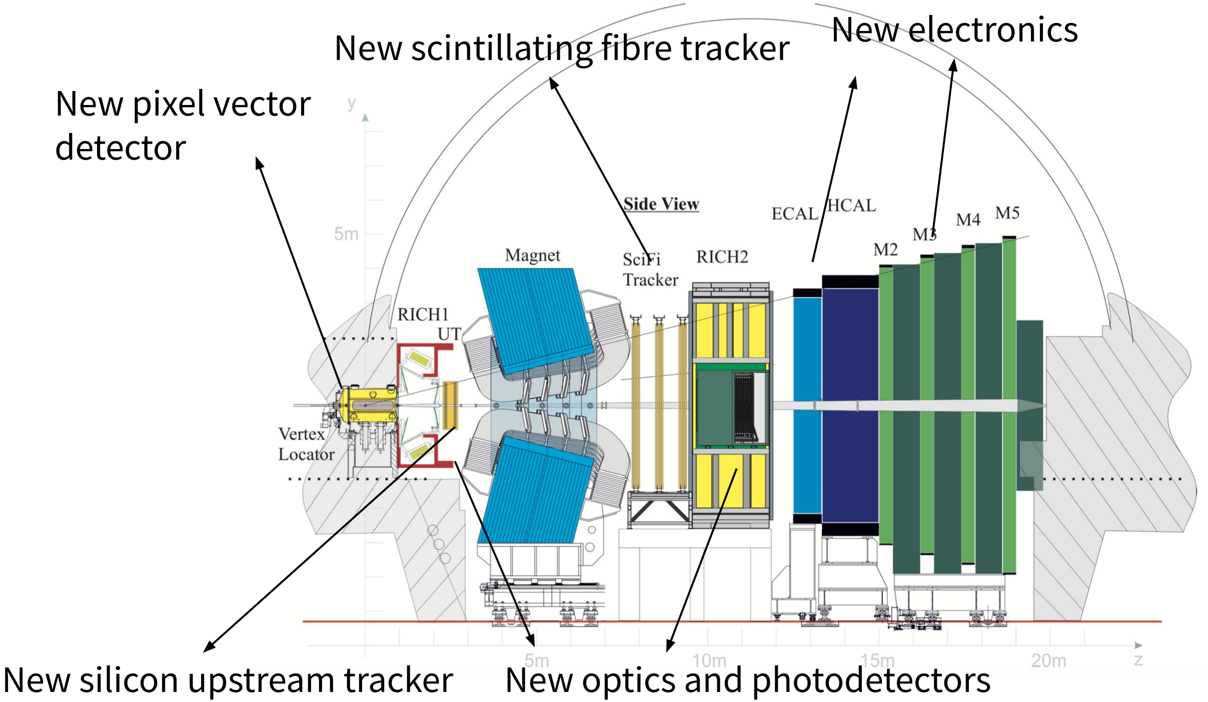


➢ 2.1-2.3 (low) and 2.4-2.5σ (central) deviation from the SM

➢ Statistically limited by the electron sample

A word about the LHCb Upgrade

Collect ~50fb^{-1}, 5x luminosity in Run 1 and Run2 combined (9fb^{-1})!



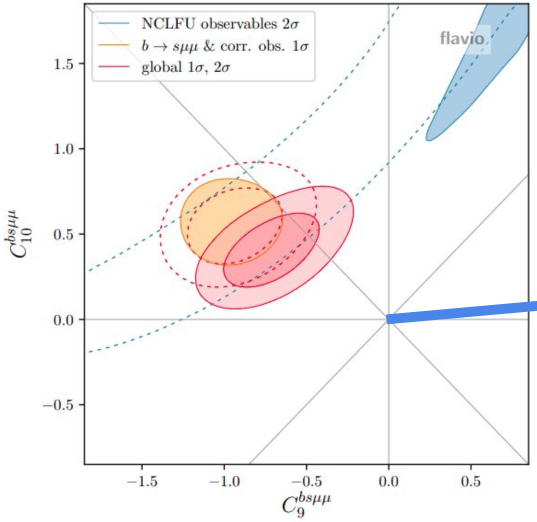
(Some) Theoretical interpretations - LFU

Model **independent** approach: $\mathcal{H}_{\text{eff}} \propto \sum_i \mathcal{C}_i \mathcal{O}_i$ → local operators

eff. couplings: **Wilson Coefficients**

$$\mathcal{C}_i \equiv \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$$

$\Longrightarrow$ Global fits to WC using flavour anomalies:

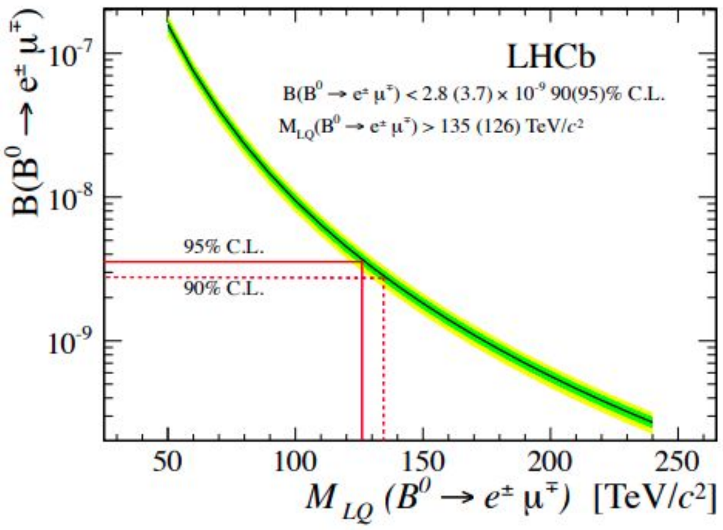


SM value

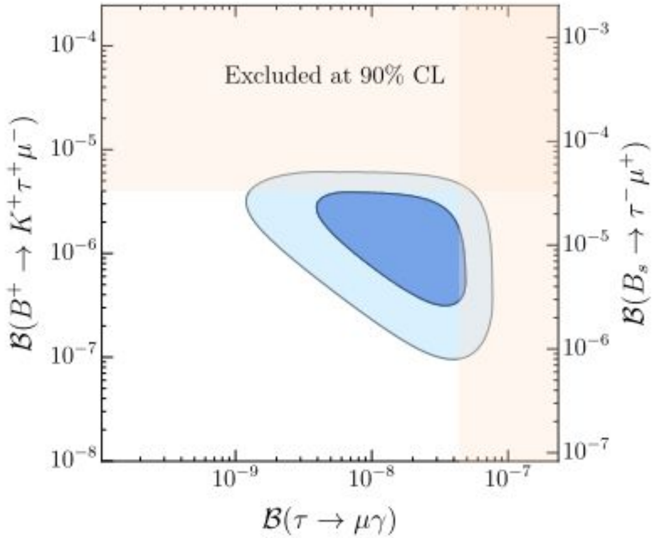
[Eur.Phys.J.C 80 (2020) 3, 252]

(Some) Theoretical implications - LFV

Effect of LFV searches in models with LQ:



[PRL 111(2013)141801]



[JHEP07(2019)168]

Electrons @ LHCb