Lepton flavour violation and universality tests at LHCb

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LHCb

Nikhef

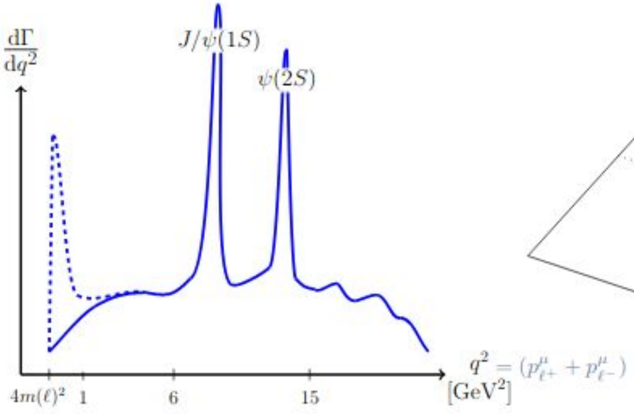
Outline

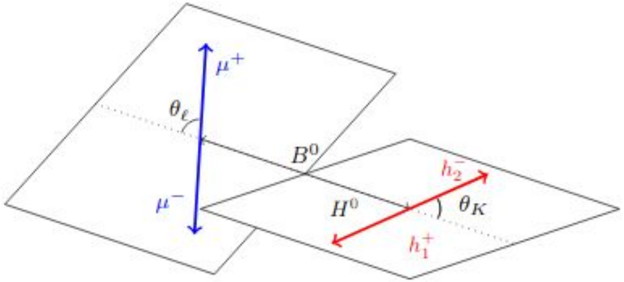
- ❖ Flavour anomalies in a nutshell
- ❖ Lepton Flavour Universality & Violation
- ❖ LFU tests
  - ➢ Semileptonic decays: R(D*)
  - ➢ Rare decays: R(K), $R(pK)^{-1}$
- ❖ LFV searches: $B^+ \to K^+\mu^\pm e^\mp$, $B^+ \to K^+\mu^-\tau^-$, $B_{(s)}{}^0 \to e^\pm\mu^\mp$, $B_{(s)}{}^0 \to \tau^\pm\mu^\mp$
- ❖ A word about the future @ LHCb
- ❖ Conclusions

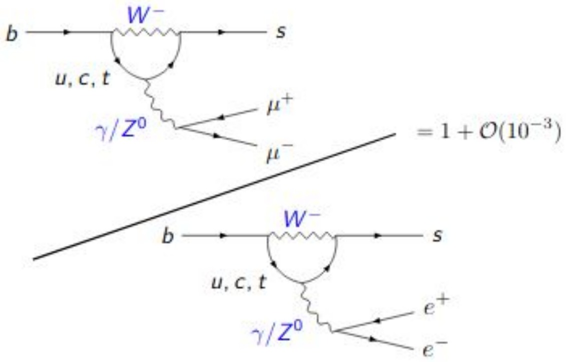
Flavour anomalies in a nutshell

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

[Branching ratios](*) [Angular distributions](*) [Lepton Flavour Universality]



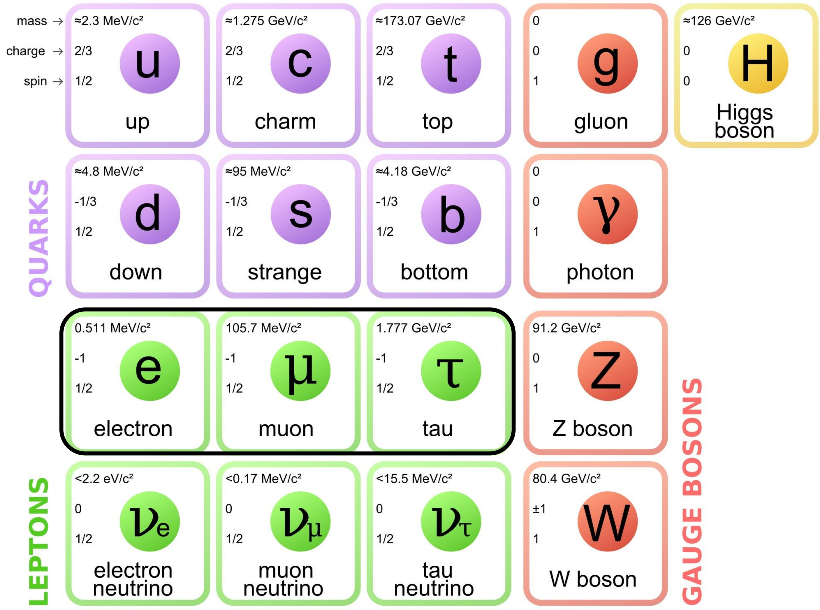




High theoretical uncertainties → Low theoretical uncertainties

(*) see talk by J. De Vries

Lepton Flavour Universality & Violation



- **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
  - Oscillations of massive neutrinos → **L**epton **F**lavour **V**iolation (**LFV**) occurs for neutrals, can mediate charged LFV in loops with BF beyond experimental reach

- **New Physics** models explaining the anomalies(*) usually feature:
  - LFU **violation** & **large** BF for LFV processes

(*) e.g. [Phys. Rev. D 92, 015007 (2015)], [Phys. Lett. B779 (2018) 317]

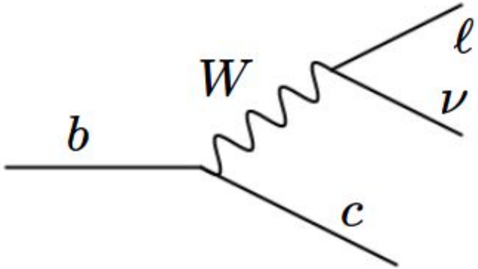
LFU tests

- Very **clean** and important **probes** of the SM and the LFU hypothesis

1. **Semileptonic decays**

   $\Longrightarrow$ Charged current decays

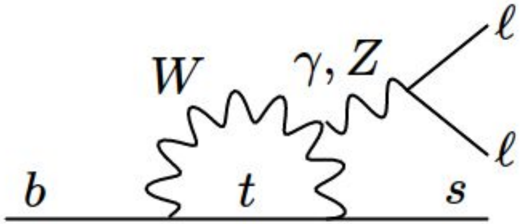
   $\Longrightarrow$ Tree level, large Branching Fraction



2. **Rare decays**

   $\Longrightarrow$ Neutral current decays

   $\Longrightarrow$ Loop level, strongly suppressed in the SM

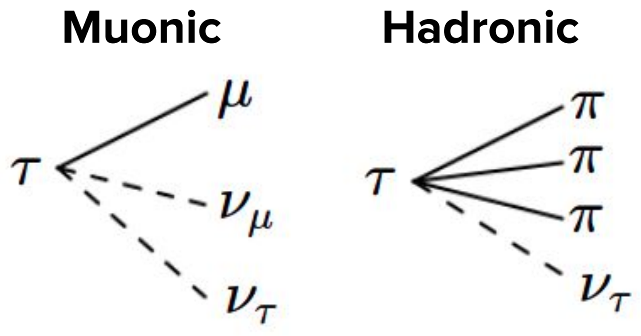


Semileptonic decays

- Compare the BF of b → c$\tau\nu_\tau$ and b → c$\mu\nu_\mu$ decays
- Hadronic uncertainties mainly cancel out → clean theory prediction in the **SM**

Experimental remarks:

1. Taus reconstructed in two ways depending on the decay: **muonic** and **hadronic**
2. For the taus, **neutrino(s)** in the final state ⟹ **challenge**
3. B-factories (BaBar, Belle) have cleaner events, but LHCb has more statistics
4. Results with Run 1 data (2011 - 2012)



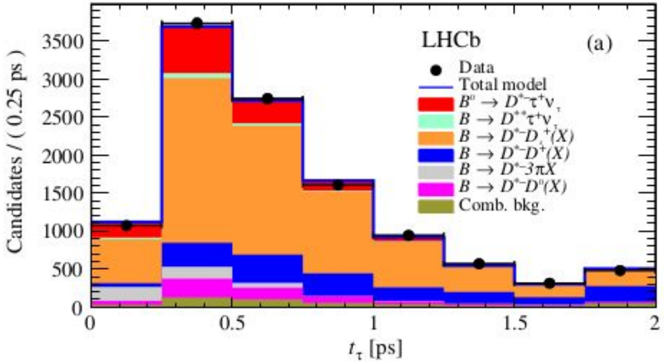
R(D*) hadronic

[PRD 97, 072013 (2018)]

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

- $B^0 \to D^{*-} 3\pi$ as **normalization** channel
- 2 main sources of **background**:
  - $B \to D^* 3\pi X$: suppressed imposing a detachment constraint of $\tau \to 3\pi$ from the B vertex
  - Double-charm decays: suppressed using a BDT
- Three-dimensional binned maximum likelihood fit to the distributions of q^2 , 3π decay time, and BDT output

$$\mathcal{R}(D^{*-}) = 0.291 \pm 0.019(\text{stat}) \pm 0.026(\text{syst}) \pm 0.013(\text{ext})$$

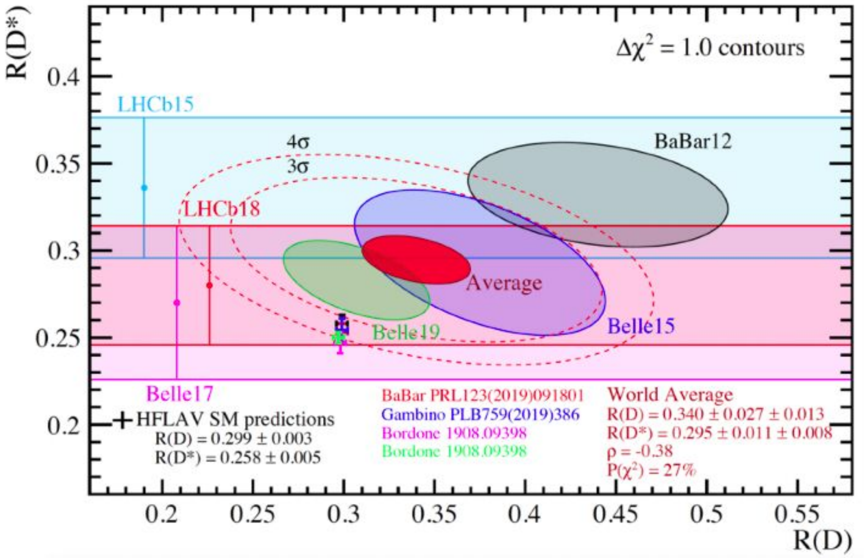


➢ ~0.9σ above the SM value
➢ compatible with the **muonic** channel
➢ systematics dominated by simulation statistics

R(D*) combination

[hflav.web.cern.ch]

Including results from **Belle** [PRD 92 (2015) 072014], [PRL 118 (2017) 211801], [arXiv:1904.08794v2] and **BaBar** [PRL 109, 101802 (2012)], [PRL 123 (2019) 091801]:



→ Global tension with SM of about **3.1σ**

Rare decays

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

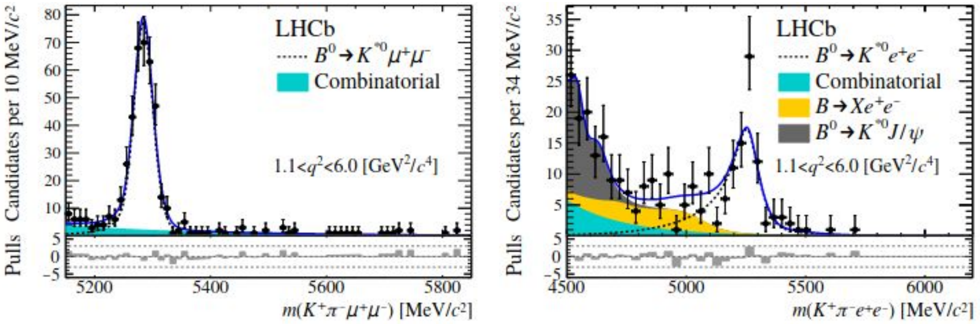
- cancellation of hadronic effects
- O(1%) radiative corrections in the central q^2 bin [1.1, 6.0] GeV^2/c^4

Measure double ratios to better control uncertainties:

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

Experimental challenges:

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



[JHEP 1708 (2017) 055]

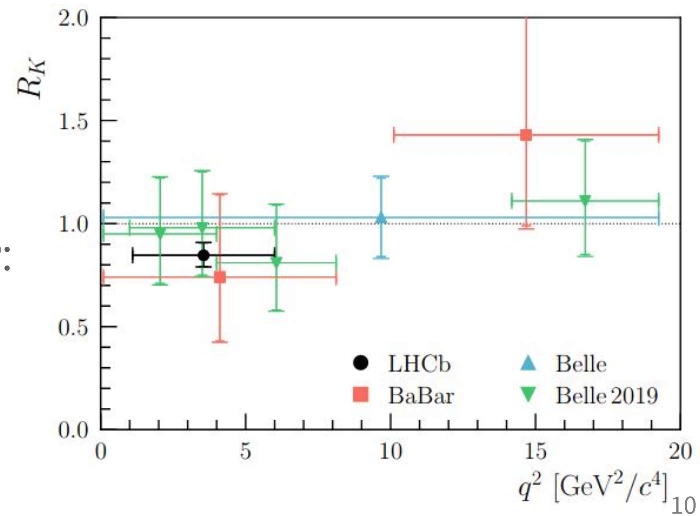
R(K)

[PRL 122 (2019) 191801]

- $X = K^+ \Longrightarrow B^+ \to K^+ e^+ e^-$, $B^+ \to K^+ \mu^+ \mu^-$
- One region of q^2: central ($1.1 < q^2 < 6.0$ GeV^2/c^4)
- Run 1 data (2011 - 2012) + Run 2 data (2015 - 2016)
  - Twice as many B^+'s as the previous measurement [PRL 113, 151601]
- Various cross-checks performed:
  - $r_{J/\psi}$ is flat for a number of reconstructed variables.
  - $r_{J/\psi} = 1.014 \pm 0.035(\text{stat} + \text{syst})$
  - $R_K^{\Psi(2S)} = 0.986 \pm 0.013(\text{stat} + \text{syst})$

➢ R(K) compatible with the SM expectation at **2.5σ**:

$$R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$$



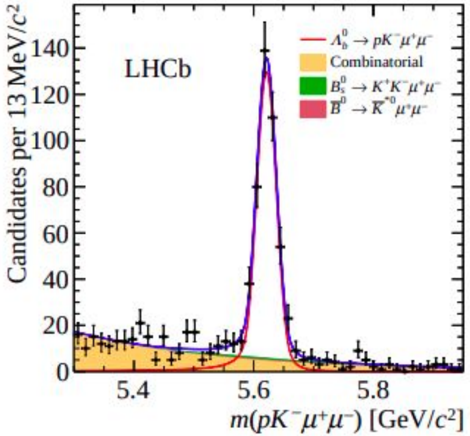
[PRD 86 (2012) 032012], [PRL 103 (2009) 171801], [arXiv:1908.01848]

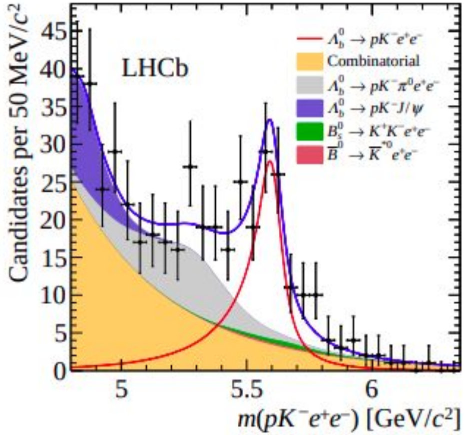
$R(pK)^{-1}$ [arXiv:1912.08139]

- $X = pK^- \Rightarrow \Lambda_b^0 \to pK^- e^+ e^-$, $\Lambda_b^0 \to pK^- \mu^+ \mu^-$
  - **First** test of LFU with *b* baryons
  - First **measurement** of the $\Lambda_b^0 \to pK^- \mu^+ \mu^-$ BF
  - First **observation** of the decay $\Lambda_b^0 \to pK^- e^+ e^-$
- Run 1 (2011-2012) + Run 2 (2016) dataset
  - $0.1 < q^2 < 6.0\ \mathrm{GeV}^2/c^4$
  - $m(pK^-) < 2600\ \mathrm{MeV}/c^2$
- Similar cross-checks as for R(K)
- Important sources of **background:**
  - Combinatorial + hadron misidentification

$$R_{pK}^{-1} = 1.17^{+0.18}_{-0.16} \pm 0.07$$

➢ Compatible with 1 within 1σ; **independent** test of the SM

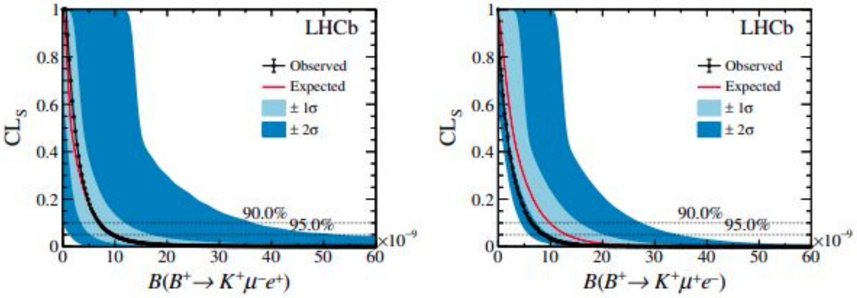




$B^+ \to K^+\mu^\pm e^\mp$ [PRL.123 (2019) 241802]

- Run 1 analysis, using $B^+ \to K^+J/\psi(\to \mu^+\mu^-)$ as **normalization** & $B^+ \to K^+J/\psi(\to e^+e^-)$ as **control** channels
    - Assumes a **uniform** distribution of signal events within the phase space
    - Most significant **background**: partially reconstructed B^+ decays (vetoed)
    - Two **BDTs** for combinatorial background & bkg from partially reconstructed b-hadron decays
- No signal excess found, upper limit @ 90% (95%) CL:

$$\mathcal{B}(B^+ \to K^+\mu^-e^+) < 7.0(9.5) \times 10^{-9}$$
$$\mathcal{B}(B^+ \to K^+\mu^+e^-) < 6.4(8.8) \times 10^{-9}$$



➢ 1 order of magnitude improvement

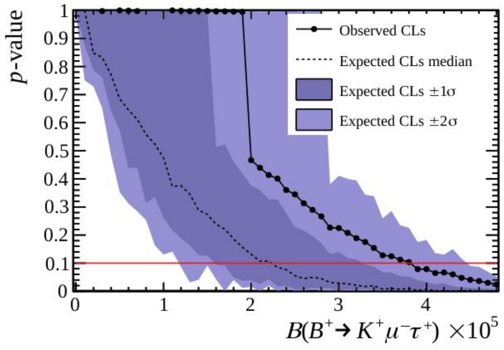
➢ Systematics dominated by simulation corrections

$B^+ \to K^+\mu^-\tau^-$ [arXiv:2003.04352]

- Run 1 (2011-2012) + Run 2 (2015-2018) analysis using $\mathbf{B^{*0}_{s2} \to B^+K^-}$ decays (1% of total B^+ production)
  - **Signal**: phase space + operators/WC from [Eur. Phys. J. C76 (2016) 134]
  - **Background**: mostly partially reconstructed b-hadron decays
  - $B^+ \to J/\psi K^+$ as **normalization** channel, with $J/\psi \to \mu^+\mu^-$
  - $m(K^+\mu^-) > 1800$ MeV → reduces bkg from **semileptonic charm** decays
  - τ selected **inclusively**, primarily via decays with a single charged particle.
- Preferred over $B^+ \to K^+\mu^+\tau^+$:
  - lower background from semileptonic decays
- No signal excess found, **world-best** upper limit:

$$\mathcal{B}(B^+ \to K^+\mu^-\tau^+) < 3.9(4.5) \times 10^{-5}$$

@ 90% (95%) CL

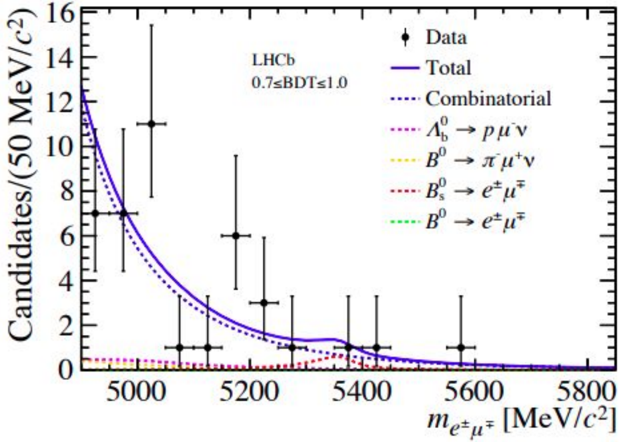


$B_{(s)}^0 \rightarrow e^{\pm}\mu^{\mp}$ [arXiv:1710.04111]

- Run 1 analysis, using $B^0 \rightarrow K^+\pi^-$ (similar topology) & $B^+ \rightarrow K^+ J/\psi(\rightarrow \mu^+\mu^-)$ (abundant yield and similar purity and trigger selection) as **normalization** channels
  - $m(e^{\pm}\mu^{\mp}) \in [4900, 5850]$ MeV/c^2
  - Simultaneous **invariant- mass fit** in 2 brem categories x 7 BDT bins, with **backgrounds:**
    - $B \rightarrow h^+h'^-$ as main **peaking** bkg → only 0.1 events survive the PID requirements
    - **Combinatorial** bkg → BDT
    - $B^0 \rightarrow \pi\mu\nu$ and $\Lambda_b^0 \rightarrow \pi\mu\nu$ (**π→e misID**) → included in the fit
- No signal excess found, **world-best** upper limit(*):

$$\mathcal{B}(B_s^0 \rightarrow e^{\pm}\mu^{\mp}) < 5.4(6.3) \times 10^{-9}$$
$$\mathcal{B}(B^0 \rightarrow e^{\pm}\mu^{\mp}) < 1.0(1.3) \times 10^{-9}$$

@ 90% (95%) CL



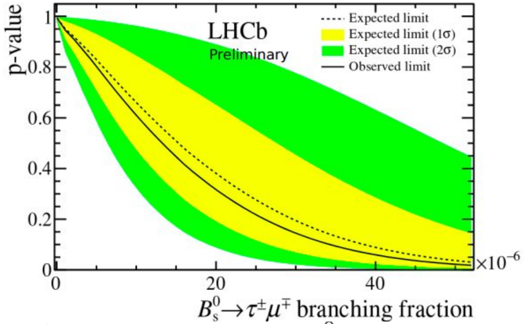
(*) dominated by heavy eigenstate for B_s^0

$B_{(s)}^0 \to \tau^{\pm}\mu^{\mp}$ [PRL 123, 211801]

- Run 1 analysis, using $\tau^- \to a_1^-(1260)\nu_\tau$, $a_1^-(1260) \to \rho^0(770)(\to \pi^+\pi^-)\pi^-$
  - $B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$ as **normalization** channel
  - **Backgrounds**:
    - Reduce with cut-based selection, e.g. decay time and masses of pion combinations
    - BDT that combines **isolation variables**: applied to reject backgrounds with extra tracks
    - Second BDT to reduce **combinatorial background**
  - Final BDT trained on MC vs SS data (full mass range) is used to **categorize** the events
  - Simultaneous maximum-likelihood fit to $M_B \in [4600, 5800]$ MeV/c^2 in 4 (final) BDT bins
- No signal excess found, upper limits(*):

$$\mathcal{B}(B^0 \to \tau^{\pm}\mu^{\mp}) < 1.2(1.4) \times 10^{-5}$$
$$\mathcal{B}(B_s^0 \to \tau^{\pm}\mu^{\mp}) < 3.4(3.5) \times 10^{-5}$$

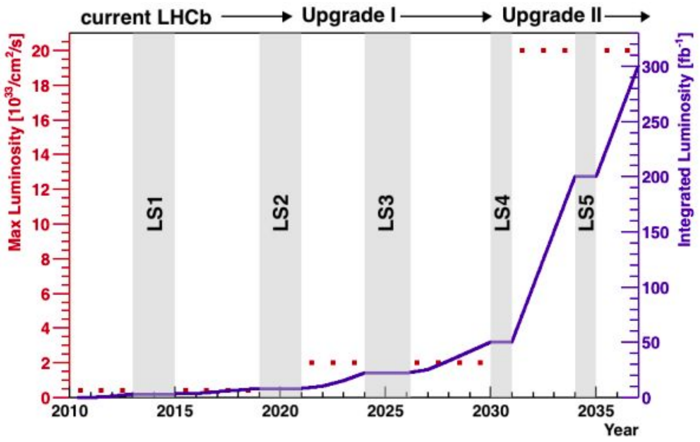
@ 90% (95%) CL



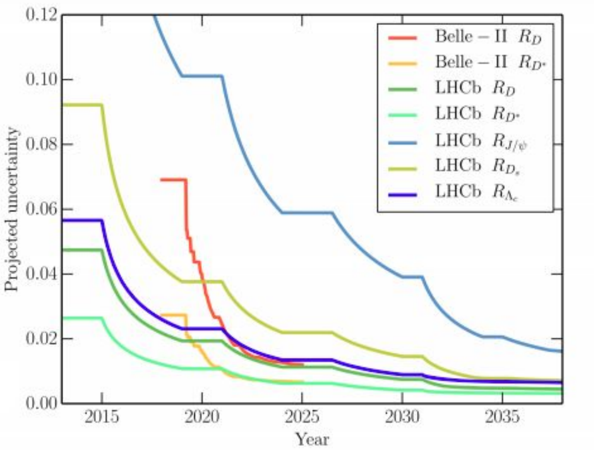
(*) B^0 limit **improves** by a factor of 2 BaBar's result [PRD 77 (2008) 091104], **first** limit on the B_s^0 mode

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**, LHCb will collect ~50fb^{-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
  - Lepton Flavour Universality tests & Lepton Flavour Violating searches are theoretically clean probes for New Physics
- Presented the latest set of results on **LFU** and **LFV** 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

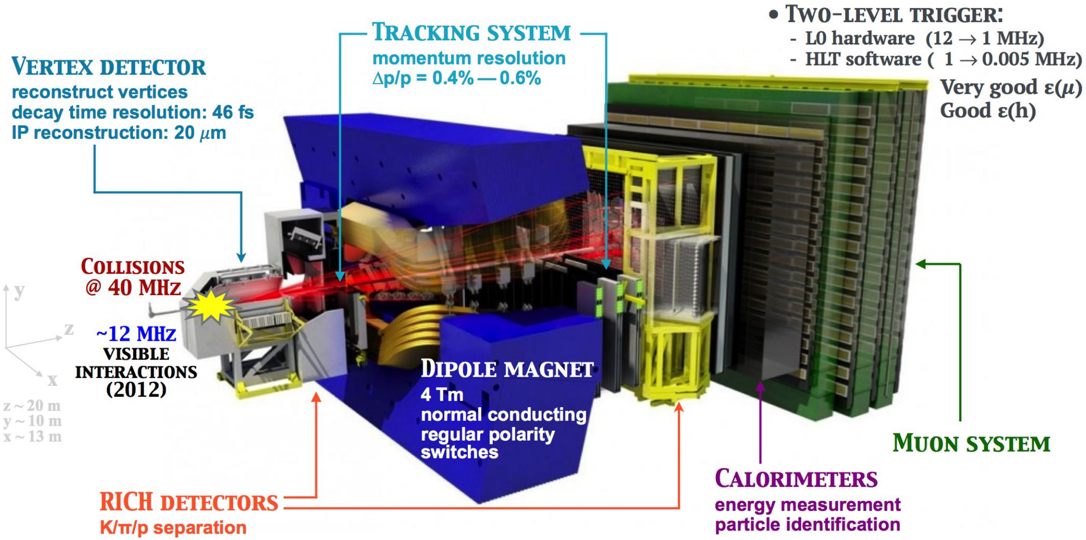
STAY TUNED!

Zoom link: https://cern.zoom.us/j/917903300095?pwd=NExBdGRsWnA1bTFXUjdUdEp4bTBUZz09; ID: 917 9033 0095

Thanks for your attention!

The LHCb detector

<u>**Single forward-arm spectrometer**</u>



- 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

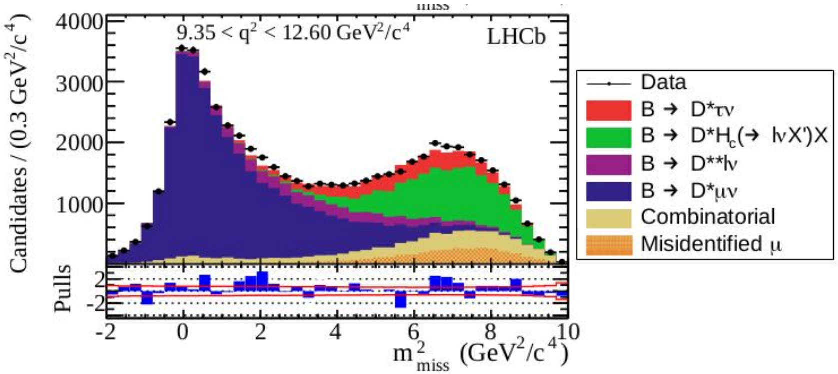
[PRL 115, (2015) no.11, 111803]

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

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

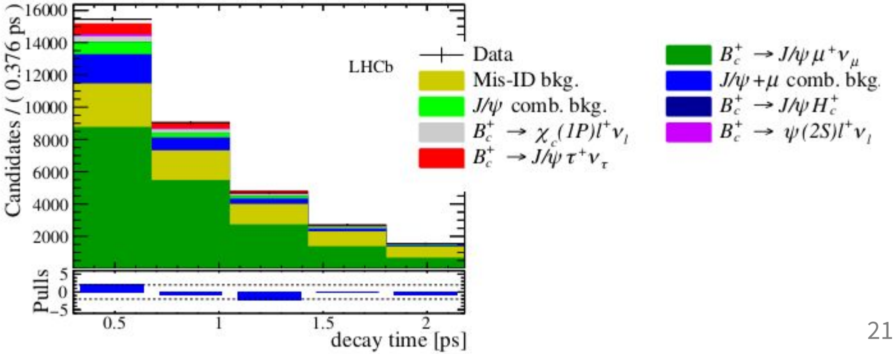
[PLB 452 (1999) 129] [arXiv:hep-ph/0211021] [PRD 73 (2006) 054024] [PRD 74 (2006) 074008]

- 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

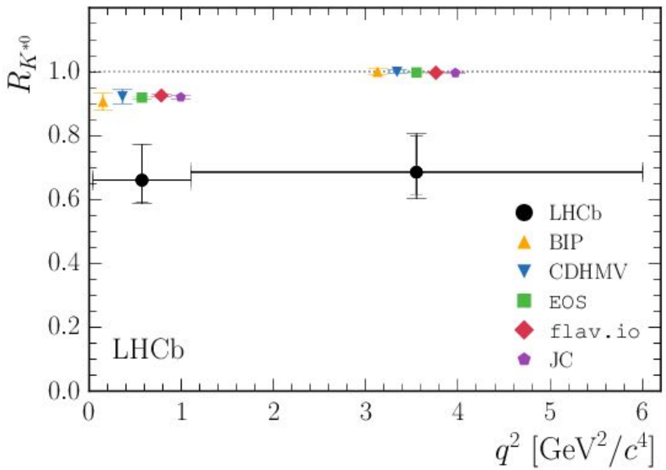


$R(K^*)$

[JHEP 1708 (2017) 055]

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

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

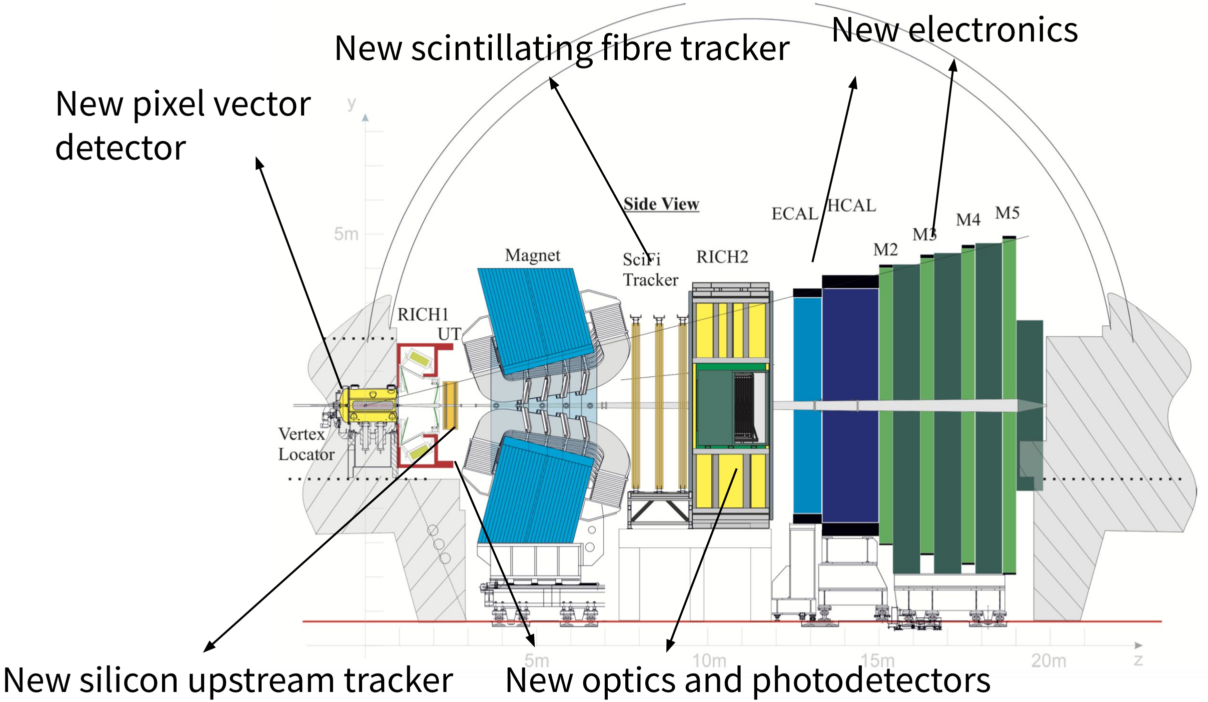


➢ 2.1-2.3 (low) and 2.4-2.5σ (central) deviation from the SM

➢ 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})!



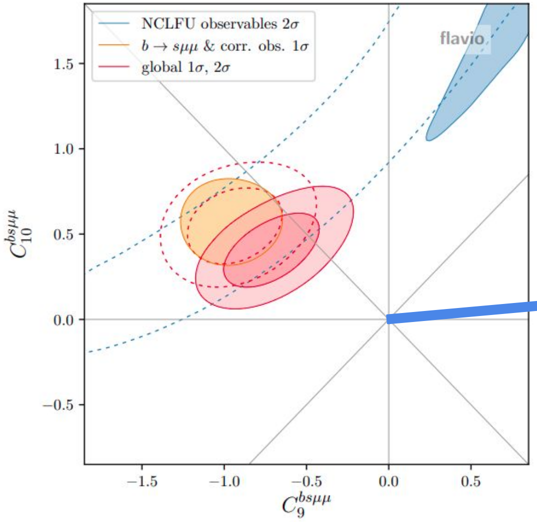
(Some) Theoretical interpretations - LFU

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

eff. couplings: **Wilson Coefficients**

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

⟹ Global fits to WC using flavour anomalies:

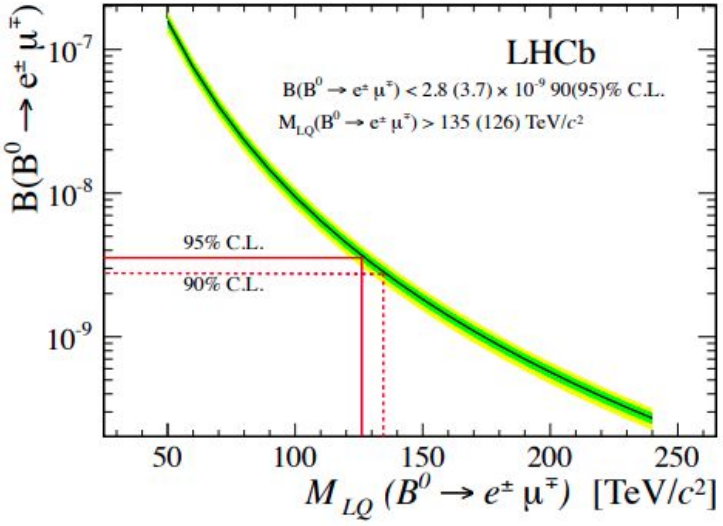


→ SM value

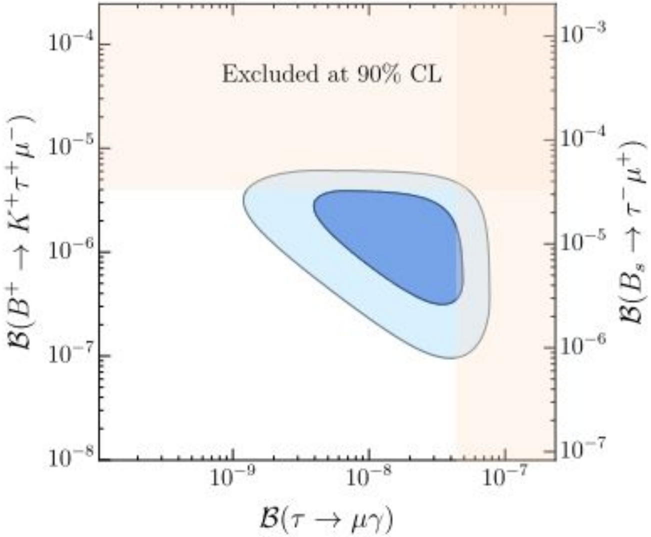
[Eur.Phys.J.C 80 (2020) 3, 252]

(Some) Theoretical implications - LFV

Effect of LFV searches in models with LQ:



[PRL 111(2013)141801]



[JHEP07(2019)168]

Electrons @ LHCb