Lepton Flavour Violation at LHCb

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On behalf of the LHCb collaboration

Implications of LHCb measurements and future prospects
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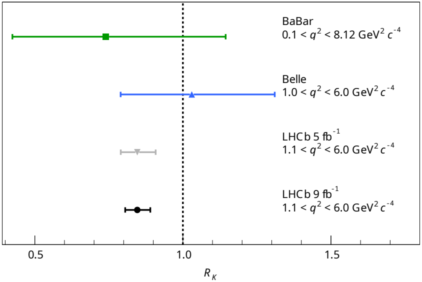
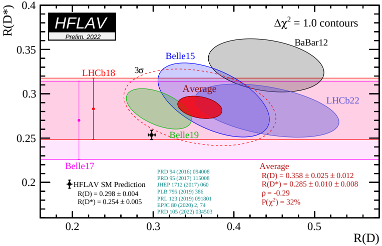
Introduction

- Lepton flavour conserved in the Standard Model
- Violated for neutral leptons via neutrino oscillations
- Tensions observed in lepton flavour universality (LFU) measurements
  - R_{K^+}, $R_{K^{*0}}$, R_{pK}, R_{K^{*+}/K^0_S} measurements in e vs. μ sector
  - R($D^{(*)}$), R(J/ψ), R(Λ_c^+) in μ vs. τ sector





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→ Theoretical models explaining LFU violation also predict lepton flavour violation (LFV) [PRL 114 (2015) 091801]

- Observation of charged LFV would be a clear sign for New Physics (NP)

Where to look

- Aforementioned LFU ratio directly motivate searches [PLB 750 (2015) 367-371], [JHEP12 (2016) 027] for
  - $b \to se\mu$
  - $b \to s\tau\mu$
- Possible in multiple channels, a selection:

$$B^0_{(s)} \to e^\pm \mu^\mp$$
$$B^+ \to K^+ e^\pm \mu^\mp$$
$$B^0 \to K^{*0} e^\pm \mu^\mp$$
$$B^0_s \to \phi e^\pm \mu^\mp$$

$$B^0_{(s)} \to \tau^\pm \mu^\mp$$
$$B^+ \to K^+ \tau^\pm \mu^\mp$$
$$B^0 \to K^{*0} \tau^\pm \mu^\mp$$

- Furthermore interest in baryon/lepton number violation from Grand Unified Theories

$\to$ Studied in $B^0_{(s)} \to p\mu^-$

Where to look

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$B^0_s \to \phi e^\pm \mu^\mp$

$B^0_{(s)} \to \tau^\pm \mu^\mp$

$B^+ \to K^+ \tau^\pm \mu^\mp$

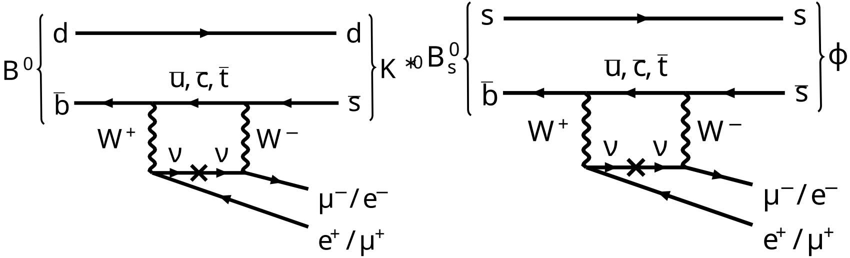
$B^0 \to K^{*0} \tau^\pm \mu^\mp$

- Furthermore interest in baryon/lepton number violation from Grand Unified Theories

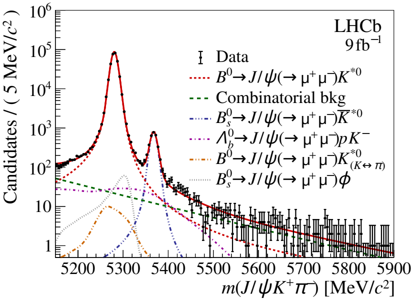
→ Studied in $B^0_{(s)} \to p \mu^-$

$B^0 \to K^{*0} e^\pm \mu^\mp$ and $B_s^0 \to \phi e^\pm \mu^\mp$ [arxiv:2207.04005]

- Analysis presented here first search in these channels at LHCb
- No published measurement for $B_s^0 \to \phi e^\pm \mu^\mp$
- $B^0 \to K^{*0} e^\pm \mu^\mp$ treated separately depending on charge configuration of $K\mu$
  - NP and backgrounds differ between charge configurations
- $K^+\pi^-$ (K^+K^-) required close to nominal K^{*0} (ϕ) mass



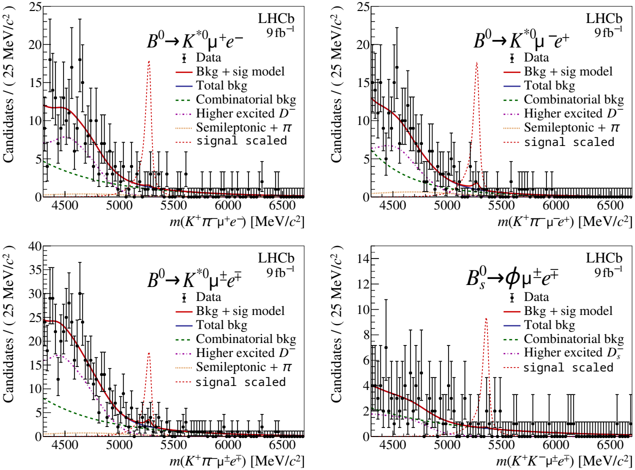
- Vetos to remove semileptonic cascades involving D mesons
- Combinatorial background removed using BDT
- Separate BDT for the K^{*0} and ϕ channels
- Backgrounds from double misidentification ($B \to (K^{*0}/\phi)\pi^+\pi^-$) reduced with requirements on particle identification
- Normalisation relative to J/ψ modes:
  - $B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-)$ and $B^0_s \to \phi J/\psi(\to \mu^+\mu^-)$



$B \to (K^{*0}/\phi)e^{\pm}\mu^{\mp}$ - Signal fit

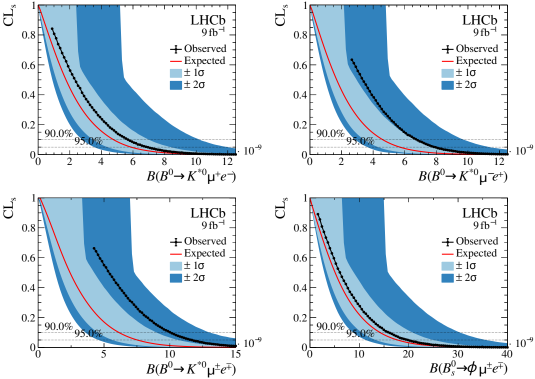
[arxiv:2207.04005]

- Remaining backgrounds in the sidebands studied in detail
- Higher excited D resonances can pass the veto requirements
  - Multiple possible modes studied and described in the fit



$B \to (K^{*0}/\phi)e^{\pm}\mu^{\mp}$ - Result

[arxiv:2207.04005]



- No significant signal observed
- Upper limits at $90(95)$ % CL determined as

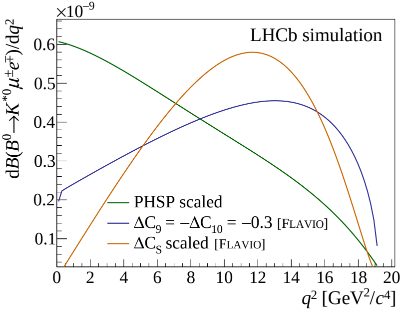
$$\mathcal{B}(B^0 \to K^{*0}e^+\mu^-) < 6.8(7.9) \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0}e^-\mu^+) < 5.7(6.9) \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0}e^{\pm}\mu^{\mp}) < 10.1(11.7) \cdot 10^{-9}$$
$$\mathcal{B}(B_s^0 \to \phi e^{\pm}\mu^{\mp}) < 16.9(19.8) \cdot 10^{-9}$$

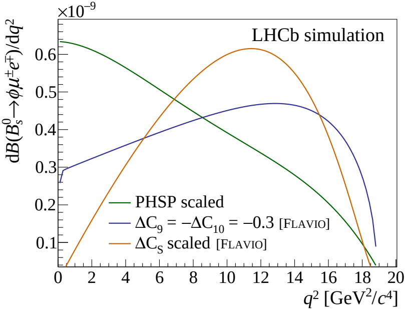
$B \to (K^{*0}/\phi) e^{\pm}\mu^{\mp}$ - NP Result

[arxiv:2207.04005]

- Above limits set assuming uniform phase space
- Distribution can differ significantly in NP models

→ Also provide limits on two specific NP scenarios





Scalar model $\mathcal{C}_9^{\mu e} \neq 0$
[EPJC 76 (2016) 134]

$$\mathcal{B}(B^0 \to K^{*0} e^+ \mu^-) < 9.9(11.5) \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0} e^- \mu^+) < 8.4(10.2) \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0} e^{\pm} \mu^{\mp}) < 14.7(17.0) \cdot 10^{-9}$$
$$\mathcal{B}(B_s^0 \to \phi e^{\pm} \mu^{\mp}) < 18.8(23.1) \cdot 10^{-9}$$

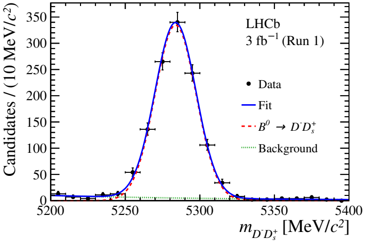
Left-handed model $\mathcal{C}_9^{\mu e} = -\mathcal{C}_{10}^{\mu e} \neq 0$
[arxiv:1810.08132]

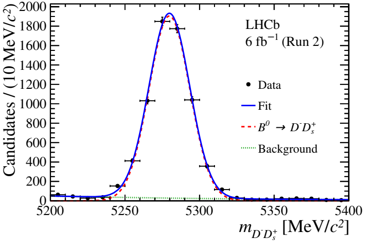
$$\mathcal{B}(B^0 \to K^{*0} e^+ \mu^-) < 8.0(9.5) \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0} e^- \mu^+) < 6.7(8.3) \cdot 10^{-9}$$
$$\mathcal{B}(B^0 \to K^{*0} e^{\pm} \mu^{\mp}) < 12.0(13.9) \cdot 10^{-9}$$
$$\mathcal{B}(B_s^0 \to \phi e^{\pm} \mu^{\mp}) < 16.5(20.5) \cdot 10^{-9}$$

$B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

[arxiv:2209.09846]

- First search for this decay by any experiment
- Separate treatment depending on $K\tau$ charge configuration
- τ^- reconstructed as $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ or $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$
  - Due to lost energy, use corrected mass $\sqrt{p_\perp^2 + m^2_{K^{*0}\tau\mu}} + p_\perp$
  - $p_\perp$: missing momentum perpendicular to B meson flight direction
- Normalisation relative to $B^0 \to D^- D_s^+$ with $D^- \to K^+\pi^-\pi^-$ and $D_s^+ \to K^+K^-\pi^+$





$B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$ - Selection

[arxiv:2209.09846]

- Two stage multivariate selection
- First BDT against combinatorial background
- Second BDT to suppress charmed mesons indentified as τ leptons
  - exploits decay topology of the τ decay
- Requirements on particle identification to remove mis-id
- K^{*0} and τ required close to their nominal mass
- Remaining partially reconstructed background reduced using Fisher discriminant based on features measuring isolation of the candidate from the event
- Lastly, physics backgrounds occuring via D^0 mesons are vetoed specifically

$B^0 \to K^{*0}\tau^\pm\mu^\mp$ - Fit setup

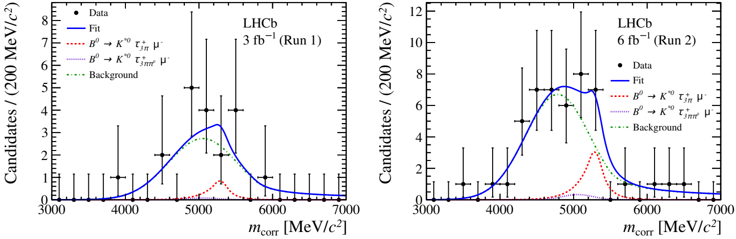
[arxiv:2209.09846]

- Fit to the data consists of three components
  - The case $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$
  - The case $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$
  - Background
- Shapes of the signal components are fixed from simulation
- Background yields are left floating
- Background shape fixed from control sample with loosened BDT selection

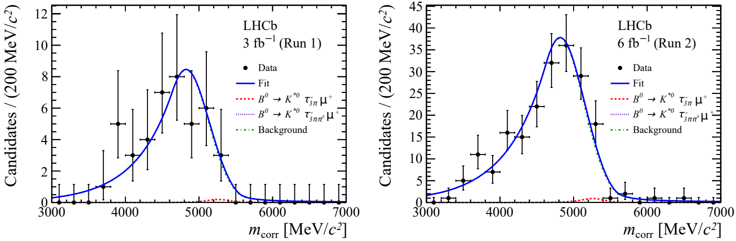
$B^0 \to K^{*0}\tau^\pm\mu^\mp$ - Final fit

[arxiv:2209.09846]

$K^{*0}\tau^+\mu^-$:

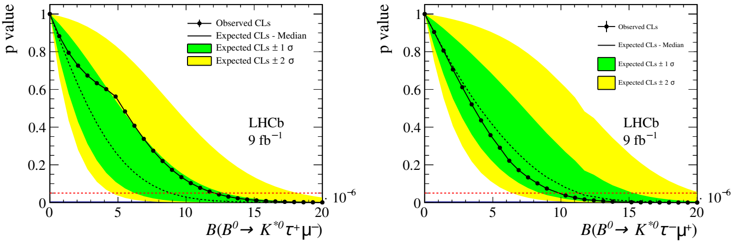


$K^{*0}\tau^-\mu^+$:



$B^0 \to K^{*0}\tau^\pm\mu^\mp$ - Results

[arxiv:2209.09846]



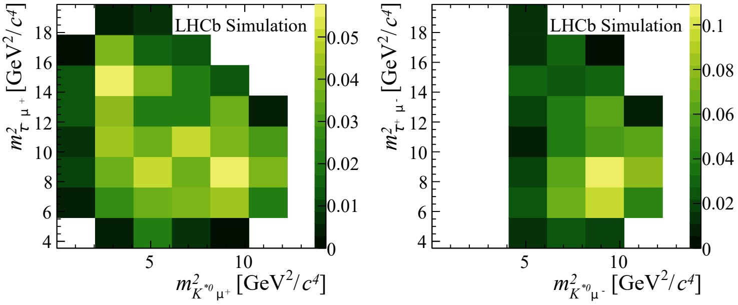
- No significant signal observed
- Upper limits at $90(95)$ % CL

$$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0(1.2)\cdot 10^{-5}$$
$$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2(9.8)\cdot 10^{-6}$$

- Most stringent limits on $b \to s\tau\mu$ transitions to date

- Limits set assuming uniform phase space
- Provide efficiencies as function of $m^2_{K^{*0}\mu}$ and $m^2_{\tau\mu}$

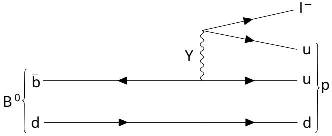
$\rightarrow$ Allows to reweight result so specific model

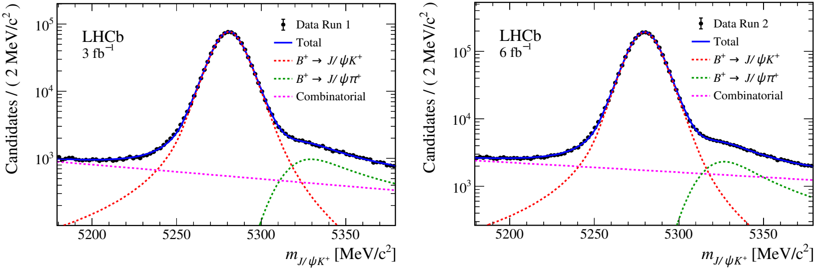


$B^0_{(s)} \to p\mu^-$

[arxiv:2210.10412]

- Baryon/Lepton number violating decay
- Strong suppression in SM ($\mathcal{O}(10^{-27})$)
- Consequence of many Grand Unified Theories
- BNV searched for by several other experiments
- First search for $B^0_{(s)} \to p\mu^-$ at LHCb
- Normalisation relative to $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$

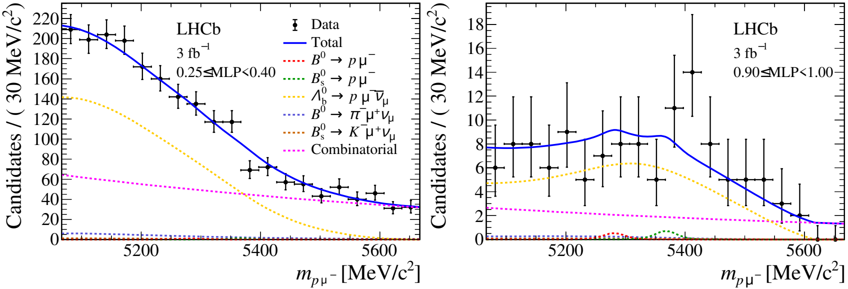


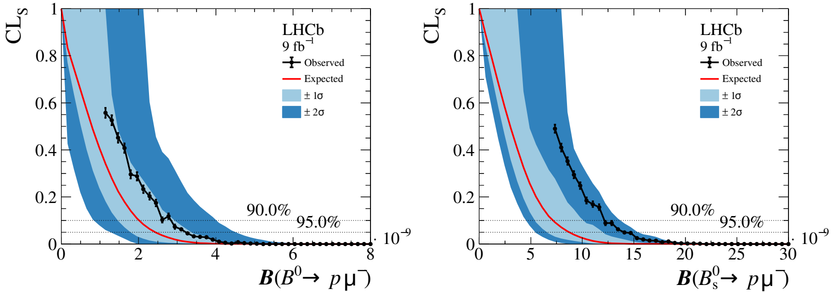


$B^0_{(s)} \to p\mu^-$ - Selection

[arxiv:2210.10412]

- Selection against combinatorial based on multilayer perceptron (MLP)
- Response calibrated based on $B^0 \to K^+\pi^-$
- Fit to extract branching fraction performed in regions of MLP response
  - lowest is discarded due to high background pollution
- Also physics backgrounds contributing
  - $X_b \to hh'$ suppressed by PID
  - Semileptonics, especially $\Lambda_b^0 \to p\mu\nu_\mu$, still contribute





- First limits on $B^0_{(s)} \to p\mu^-$

$$\mathcal{B}(B^0 \to p\mu^-) < 2.6(3.1) \cdot 10^{-9} \text{ @90(95) \% CL}$$
$$\mathcal{B}(B^0_s \to p\mu^-) < 1.2(1.4) \cdot 10^{-8} \text{ @90(95) \% CL}$$

Run 3 prospects

- Run 3 will bring lots of new data
- Also more flexible trigger system
- Opportunity to
  - increase sensitivity on already studied modes
  - broaden our LFV program
- Many additional LFV selection requirements prepared, including

$B^0 \to K^0_S e\mu$

$B^+ \to \pi^+ e\mu$

$B^0_{(s)} \to \tau e$

$B^0_s \to \phi\mu\tau$

$\Lambda^0_b \to pKe\mu$

$\Lambda^0_b \to \Lambda e\mu$

$\Lambda^0_b \to pK\mu\tau$

- Suggestion for additional channels to explore are always welcome
- Which BNV should we explore further that are not excluded by proton decay limits?

Summary

- LFV, together with LFU, provides an interesting probe for NP
- LHCb provides ideal environment for these searches
- No evidence for LFV yet, but stringent limits set
- Several analyses with current data ongoing
- New data from Run 3 will improve sensitivity and allow for many additional searches
- Excitement for LFV not LHCb exclusive, e.g. recent Belle results [JHEP 03 (2021) 105]

Thank you for your attention