

B Violation, *L* Violation and Lepton Flavour Violation at LHCb

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On behalf of the LHCb Collaboration

2022 International Workshop on Baryon and Lepton Number Violation
Brussels, Belgium – September 5th, 2022

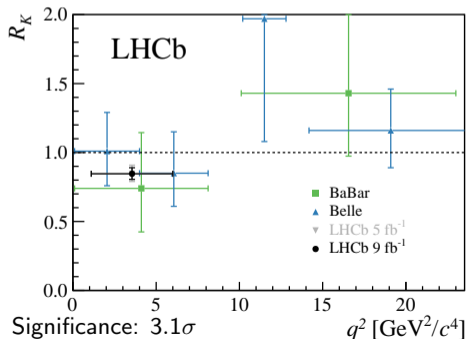


From $b \rightarrow sll$ Flavour Anomalies to Lepton Flavour Violation

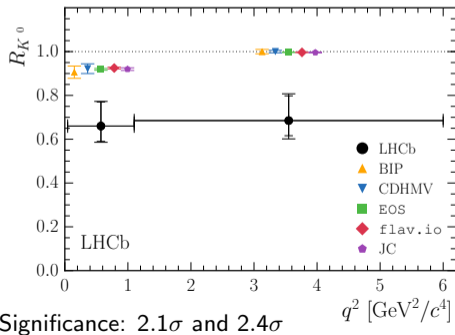
Test of Lepton Flavour Universality

$$R_K = \frac{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d}{dq^2} B(B^+ \rightarrow K^+ \mu^+ \mu^-) dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d}{dq^2} B(B^+ \rightarrow K^+ e^+ e^-) dq^2} \stackrel{\text{SM}}{=} 1$$

LHCb-PAPER-2021-004

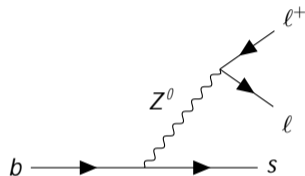


LHCb-PAPER-2017-013

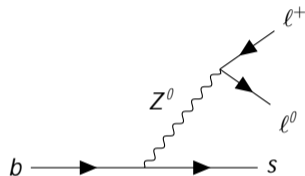


From $b \rightarrow s \ell \ell$ Flavour Anomalies to Lepton Flavour Violation

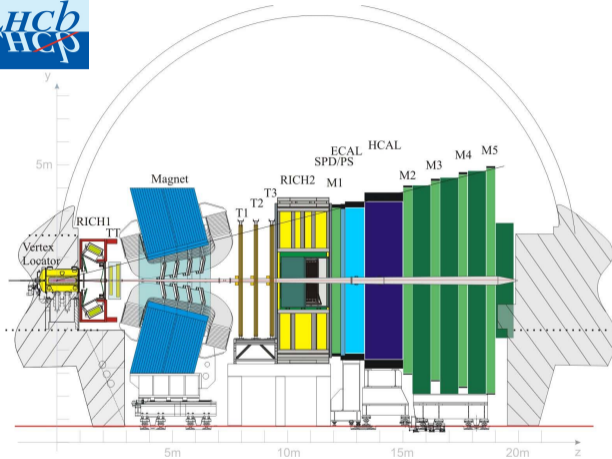
Lepton Flavour Universality Violation



Lepton Flavour Violation



- | Beyond the Standard Model physics introduced to explain LFUV in $b \rightarrow s \ell \ell$ transitions ...
... also predicts strongly enhanced LFV effects in $b \rightarrow s \ell \ell^0$ transitions
[Glashow, Guadagnoli, Lane, arXiv:1411.0565]
- | Strong motivation the search for $b \rightarrow s \mu e$ and $b \rightarrow s \tau \mu$ transitions
- | B meson decays ideally suited for these searches



Extensive Physics Programme

- | CP Violation
- | Rare Decays
- | Forward EW Physics
- | Spectroscopy
- | $p+p$, $p+Pb$, $Pb+Pb$
- | ...

Data Collected

- | Run 1:
 - | 2011: 1 fb⁻¹ at 7 TeV
 - | 2012: 2 fb⁻¹ at 8 TeV
- | Run 2:
 - | 2015 to 2018: 6 fb⁻¹ at 13 TeV

Forward arm spectrometer to study b- and c-hadron decays

- | Pseudo-rapidity coverage: $2 < \eta < 5$

Overview of LHCb Results

Lepton Flavour Violation

	90% C.L. Limit	Data	Reference
B_s^0	$\mathcal{B}(B_s^0 \rightarrow \tau \mu) < 3.4 \times 10^{-5}$	3 fb ¹	LHCb-PAPER-2019-016
	$\mathcal{B}(B_s^0 \rightarrow e \mu) < 5.4 \times 10^{-9}$	3 fb ¹	LHCb-PAPER-2017-031
B_d^0	$\mathcal{B}(B_d^0 \rightarrow \tau \mu) < 1.2 \times 10^{-5}$	3 fb ¹	LHCb-PAPER-2019-016
	$\mathcal{B}(B_d^0 \rightarrow e \mu) < 1.0 \times 10^{-9}$	3 fb ¹	LHCb-PAPER-2017-031
B^+	$\mathcal{B}(B^+ \rightarrow K^+ \mu \tau^+) < 3.9 \times 10^{-5}$	9 fb ¹	LHCb-PAPER-2019-043
	$\mathcal{B}(B^+ \rightarrow K^+ \mu e^+) < 7.0 \times 10^{-9}$	3 fb ¹	LHCb-PAPER-2019-022
	$\mathcal{B}(B^+ \rightarrow K^+ \mu^+ e) < 6.4 \times 10^{-9}$	3 fb ¹	LHCb-PAPER-2019-022
D^0	$\mathcal{B}(D^0 \rightarrow e \mu) < 1.3 \times 10^{-8}$	3 fb ¹	LHCb-PAPER-2015-048
τ	$\mathcal{B}(\tau \rightarrow \mu \mu^+ \mu) < 4.6 \times 10^{-8}$	3 fb ¹	LHCb-PAPER-2014-052
	$\mathcal{B}(\tau \rightarrow \bar{\rho} \mu^+ \mu) < 3.3 \times 10^{-7}$	1 fb ¹	LHCb-PAPER-2013-014
	$\mathcal{B}(\tau \rightarrow \rho \mu \mu) < 4.4 \times 10^{-7}$	1 fb ¹	LHCb-PAPER-2013-014

Lepton Number Violation

	90% C.L. Limit	Data	Reference
B^+	$\mathcal{B}(B^+ \rightarrow K \mu^+ \mu^+) < 4.1 \times 10^{-8}$	36 pb ¹	LHCb-PAPER-2011-009
	$\mathcal{B}(B^+ \rightarrow \pi \mu^+ \mu^+) < 4.4 \times 10^{-8}$	36 pb ¹	LHCb-PAPER-2011-009

Lepton Flavour Violation

1 Search for $B_d^0 \rightarrow K^0 \mu e$ and $B_s^0 \rightarrow \phi \mu e$

LHCb-PAPER-2022-008

2 Search for $B_d^0 \rightarrow K^0 \tau \mu$

to appear in LHCb-PAPER-2022-021

Baryon and Lepton Number Violation

3 Search for $B_d^0 \rightarrow p \mu$ and $B_s^0 \rightarrow p \mu$

to appear in LHCb-PAPER-2022-022

- | Measure relative to known B meson decay

$$B(\text{Signal Mode}) = B(\text{Normalisation Mode}) \frac{1}{N_{\text{norm}}} \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}} N_{\text{sig}}$$

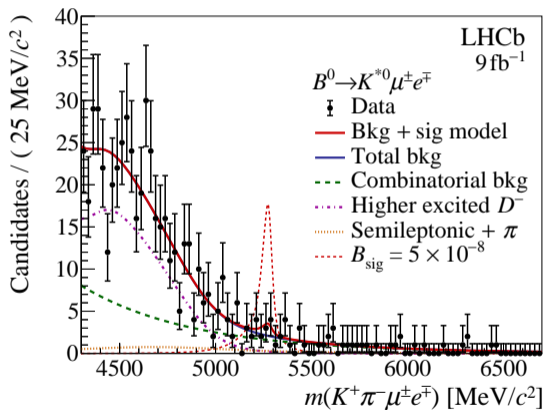
- | Each search involves the same steps:

- 1 Event selection + fit to data) Number of signal events N_{sig}
- 2 Separate analysis of normalisation mode) Number of events N_{norm}
- 3 Selection efficiencies and systematic uncertainties) Ratio of efficiencies $\epsilon_{\text{norm}}/\epsilon_{\text{sig}}$
- 4 External input) $B(\text{Normalisation Mode})$

- | All three searches use full Run 1+2 data sample (9 fb^{-1})

Search for $B_d^0 \rightarrow K^0 \mu e$ and $B_s^0 \rightarrow \phi \mu e$

- 1 Misreconstructed background from $B_d^0 \rightarrow \psi(nS)(\ell^+\ell^-)K^0$ and $B_s^0 \rightarrow \psi(nS)(\ell^+\ell^-)\phi$
 - 1 One of the leptons from the J/ψ or $\psi(2S)$ is misidentified: $(\ell^+\ell^0)$
 - ▶ Veto the B_d^0 mass range in the $K^+\pi^- J/\psi$ and $K^+\pi^- \psi(2S)$ invariant mass distributions
 - ▶ Veto the B_s^0 mass range in the $K^+K^- J/\psi$ and $K^+K^- \psi(2S)$ invariant mass distributions
 - 2 Double misID of one meson plus one lepton: $(h^+\ell^-)$
 - ▶ Veto the K^0 mass range in the $K\ell_{\pi^+ \ell^-}$ and $\pi\ell_{K^+ \ell^-}$ invariant mass distributions
 - ▶ Veto the ϕ mass range in the $K\ell_{K^+ \ell^-}$ invariant mass distribution
- 2 Partially reconstructed background from $B_d^0 \rightarrow D^{(*)}\ell^+\nu_\ell$ and $B_s^0 \rightarrow D_s^{(*)}\ell^+\nu_\ell$
 - | Eliminated by the requirement $m(K^+\pi^-\ell^-) > 2\text{ GeV}/c^2$ and $m(K^+K^-\ell^-) > 2\text{ GeV}/c^2$
- 3 Partially reconstructed background from $B_d^0 \rightarrow D_2\ell^+\nu_\ell$ and $B_s^0 \rightarrow D_{s2}\ell^+\nu_\ell$
 - | Dominant contributions from $B_d^0 \rightarrow D_2(2460)\ell^+\nu_\ell$ and $B_s^0 \rightarrow D_{s2}(2573)\ell^+\nu_\ell$
 - | Background is modelled in the fit to data
- 4 Combinations of $B^+ \rightarrow \bar{D}^0(K^+\ell^-\bar{\nu}_\ell)\ell^0\nu_{\ell^0}$ and random pion
 - | Only affects $B_d^0 \rightarrow K^0\mu^+e^-$
 - | Background is modelled in the fit to data
- 5 Combinatorial Background
 - | Background is modelled in the fit to data



Fit Model

- | **Signal:** Sum of 2 Crystal Ball functions
 - | Shape parameters taken from simulation
 - | Mass resolution corrected using $B_d^0 \rightarrow J/\psi(\mu^+ \mu^-) K^0$ and $B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \phi$
- | **Partially reconstructed Bkgs:** Model with KDE based on simulation
- | **Combinatorial Bkg:** Single exponential
- | Simultaneous fit to 3 data taking periods:
 - 1 Run 1: 2011+2012
 - 2 Run 2a: 2015+2016
 - 3 Run 2b: 2017+2018
- | No excess found) Set an upper limit

1 Branching fraction of normalisation mode

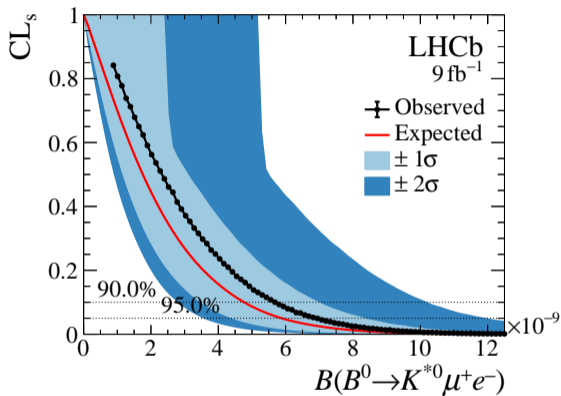
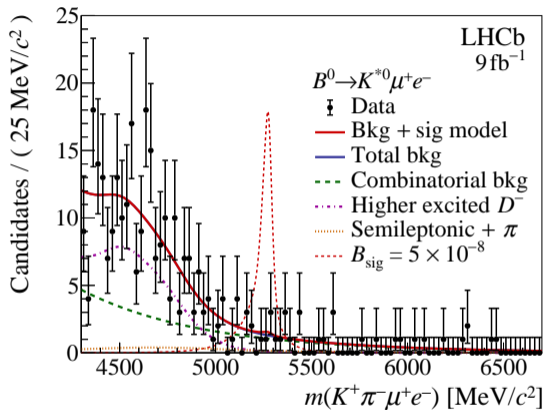
- | For $B_d^0 \rightarrow K^0 \mu^+ \mu^-$ this is $B_d^0 \rightarrow J/\psi(\mu^+ \mu^-) K^0$: Effect is 4.0%
- | For $B_s^0 \rightarrow \phi \mu^+ \mu^-$ this is $B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \phi$: Effect is 4.8%
- | These are also potential backgrounds and are explicitly vetoed in the selection of signal candidates

2 Decay time distribution of $B_s^0 \rightarrow \phi \mu^+ \mu^-$

- | Because B_s meson decay width difference $\Delta\Gamma_s \neq 0$
- | Heavy and light mass eigenstates have different lifetimes, and thus different selection efficiencies
- | Unknown mixture of the heavy and light mass eigenstates impacts the time-integrated branching fraction
- | Effect is 3.8% to 4.5%

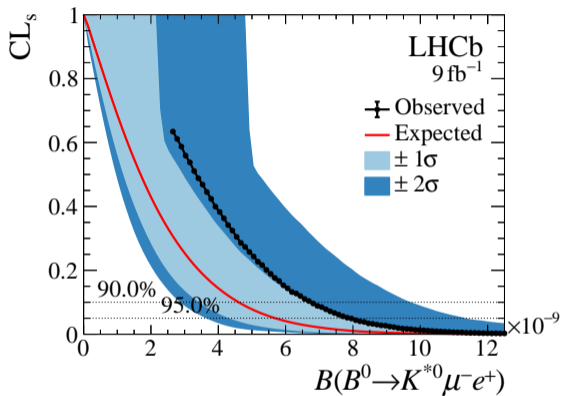
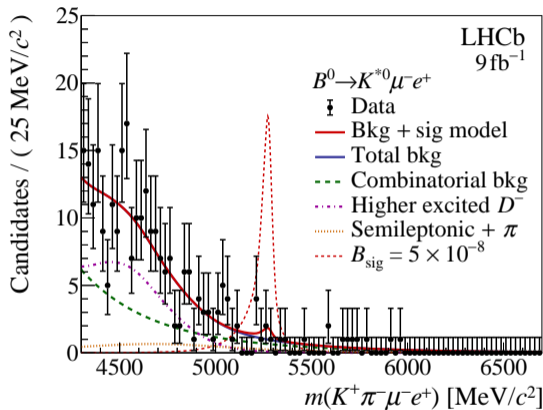
3 Total relative systematic uncertainty

- | For $B_d^0 \rightarrow K^0 \mu^+ \mu^-$: 5.2% to 6.7% (depending on data taking period)
- | For $B_s^0 \rightarrow \phi \mu^+ \mu^-$: 6.9% to 8.5% (depending on data taking period)



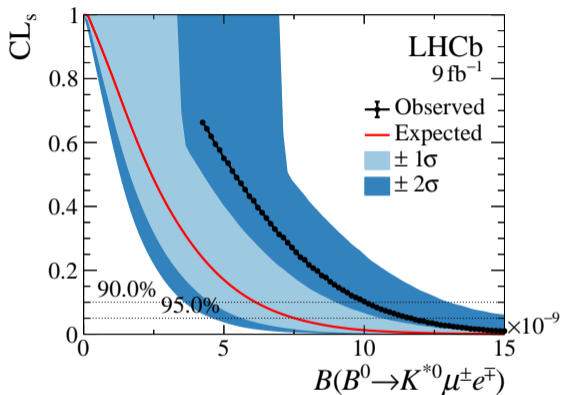
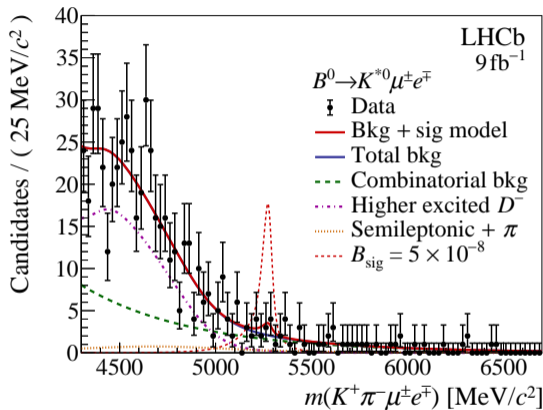
Observed Limit:
 $B(B_d^0 \rightarrow K^{*0} \mu^+ e^-) < 5.7 \times 10^{-9}$ at 90% C.L.

Expected Limit:
 $B(B_d^0 \rightarrow K^{*0} \mu^+ e^-) < 4.8 \times 10^{-9}$ at 90% C.L.

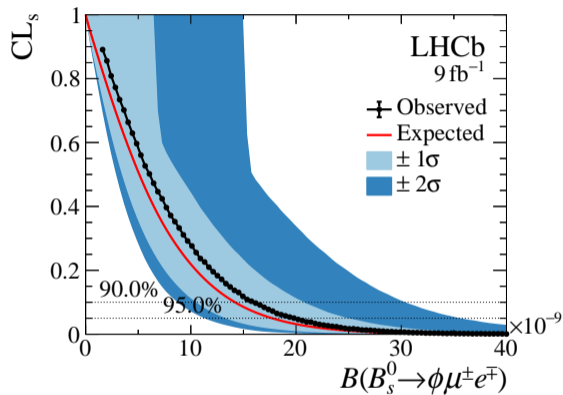
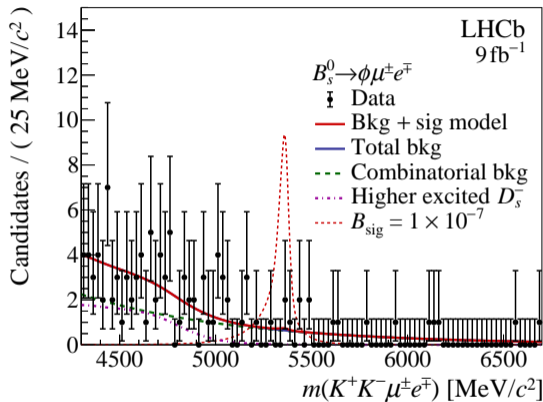


Observed Limit:
 $B(B_d^0 \rightarrow K^{*0} \mu^- e^+) < 6.8 \times 10^{-9}$ at 90% C.L.

Expected Limit:
 $B(B_d^0 \rightarrow K^{*0} \mu^- e^+) < 4.6 \times 10^{-9}$ at 90% C.L.



- | Observed Limit:
 $B(B_d^0 \rightarrow K^0 \mu^+ e^-) < 10.1 \cdot 10^{-9}$ at 90% C.L.
- | Expected Limit:
 $B(B_d^0 \rightarrow K^0 \mu^+ e^-) < 6.1 \cdot 10^{-9}$ at 90% C.L.



- Observed Limit:
 $B(B_s^0 \rightarrow \phi \mu^\pm e^\mp) < 16.0 \times 10^{-9}$ at 90% C.L.
- Expected Limit:
 $B(B_s^0 \rightarrow \phi \mu^\pm e^\mp) < 14.2 \times 10^{-9}$ at 90% C.L.

Search for $B_d^0 \rightarrow K^0 \tau \mu$

τ Lepton

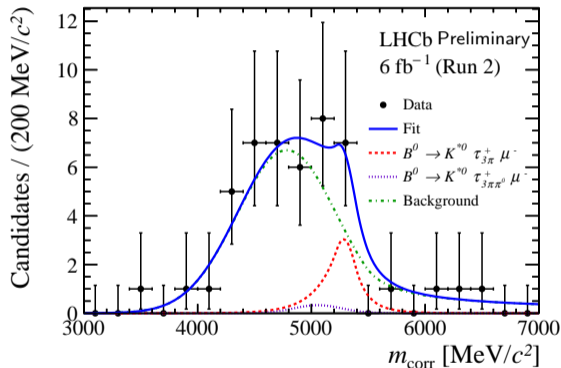
- | τ lepton is short-lived and decays before reaching the detector
- | Only reconstruct $\tau \rightarrow \pi \pi^+ \pi \nu_\tau$ and $\tau \rightarrow \pi \pi^+ \pi \pi^0 \nu_\tau$
- | Introduces additional challenges:
 - 1 Loss of statistics: selected τ decays have a combined branching fraction of only 14%
 - 2 Neutrinos escape undetected: no clear peak in the invariant mass distribution

Corrected Mass

- | Missing information: momentum of the neutrino
- | ... but it must balance momentum of $K \mu$ system in the B rest frame
- | Partially recover using observable

$$m_{\text{corr}} = \sqrt{p_\perp^2 + m_{K \mu}^2} + p_\parallel$$

- | p_\perp is the component of the missing momentum perpendicular to flight direction of the B meson
- | Signal peaks in m_{corr} , but limited resolution



Fit Model

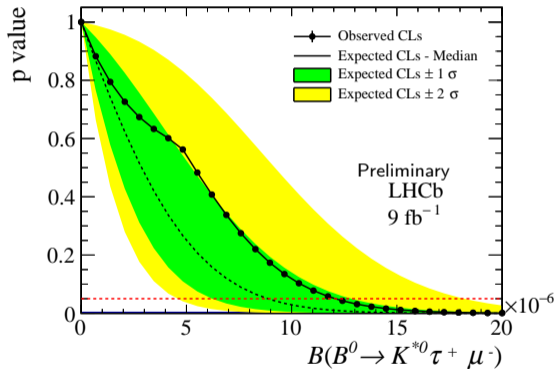
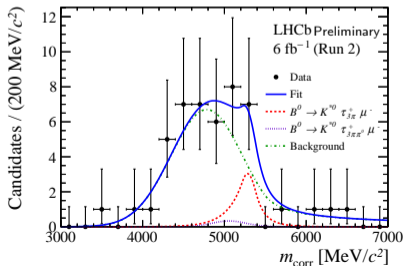
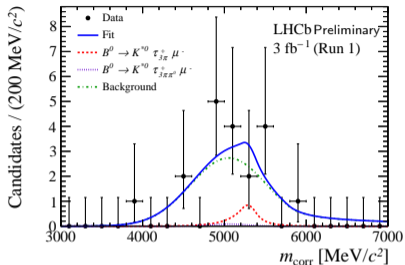
- | **Signals:** double-sided Crystal Ball function
 - | Shape parameters taken from simulation
- | **Background:** double-sided Crystal Ball function
 - | Main sources:
 - For $B_d^0 ! K^0 \tau^+ \mu^+$: $B_d^0 ! D^+ \mu^+ \nu_\mu$
 - For $B_d^0 ! K^0 \tau^+ \mu^-$: $B_d^0 ! D^+ \tau^+ \nu_\tau$
 - | Shape parameters taken from a fit to data using dedicated control region
- | Simultaneous fit to 2 data taking periods:
 - 1 Run 1: 2011+2012
 - 2 Run 2: 2015 to 2018
- | $B_d^0 ! K^0 \tau^+ \mu^-$ and $B_d^0 ! K^0 \tau^+ \mu^+$ are fitted independently
- | No excess found) Set an upper limit

1 Choice of control region for background modelling

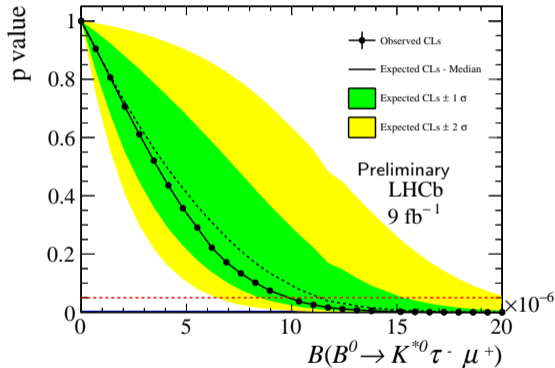
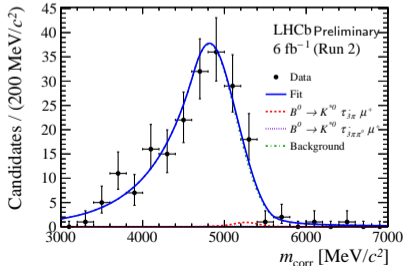
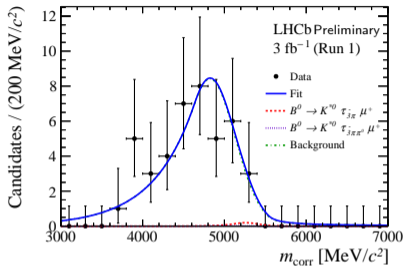
- | Select control region by relaxing the MVA requirement that suppresses combinatorial background
- | Signal contamination for $B(B_d^0 \rightarrow K^0 \tau^+ \mu^-) = 10^{-5}$ is $< 5\%$
- | Background shape parameters varied using alternative control regions
- | This impacts limit by 18% to 26%

2 Branching fraction of normalisation Mode

- | $B_d^0 \rightarrow D^- D_s^+$ with $D^- \rightarrow K^+ \pi^- \pi^0$ and $D_s^+ \rightarrow K^+ K^- \pi^+$
- | Increases limit by 3% to 4%

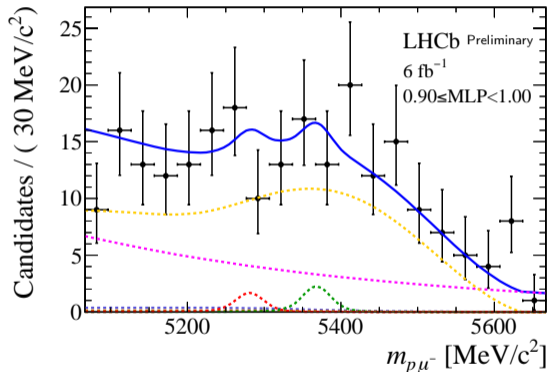


Observed Limit:
 $B(B_d^0 \rightarrow K^{*0} \tau^+ \mu^-) < 1.0 \times 10^{-5}$ at 90% C.L.



Observed Limit:
 $B(B_d^0 \rightarrow K^0 \tau \mu^+) < 8.2 \times 10^{-6}$ at 90% C.L.

Search for $B_d^0 \rightarrow p\mu$ and $B_s^0 \rightarrow p\mu$



Fit Model

Signals:

double-sided Crystal Ball function + Gaussian

Physics Bkg:

Shapes taken from simulation

Primarily: $\Lambda_b \rightarrow p\mu\bar{\nu}_\mu$

Additional minor contributions:

$B_d^0 \rightarrow \pi\mu^+\nu_\mu$ and $B_s^0 \rightarrow K\mu^+\nu_\mu$

Combinatorial Bkg: Single exponential

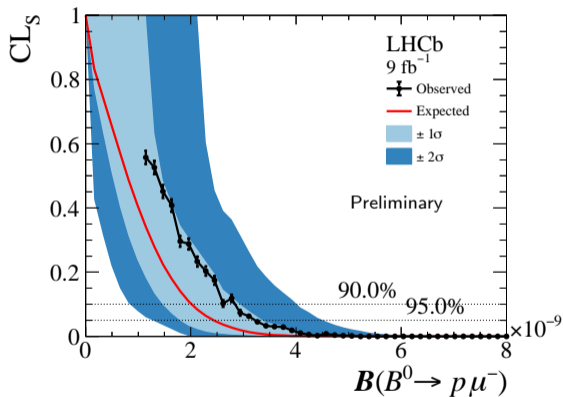
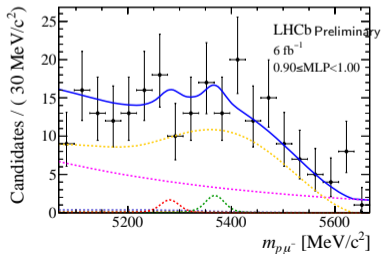
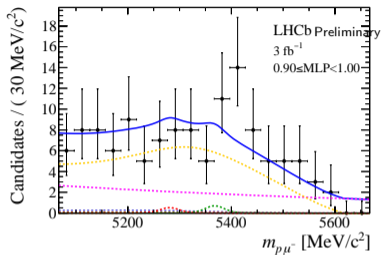
Simultaneous fit to 2 data taking periods:

1 Run 1: 2011+2012

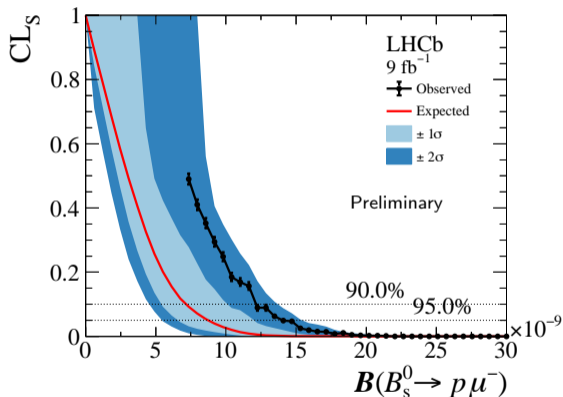
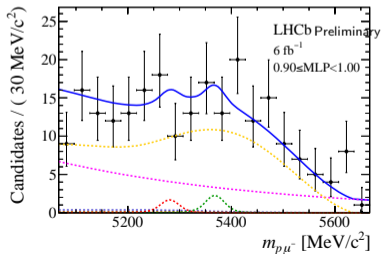
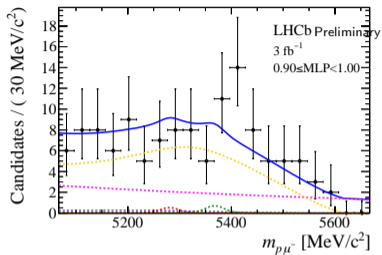
2 Run 2: 2015 to 2018

... and 7 MVA bins

No excess found) Set an upper limit



Observed Limit:
 $B(B_d^0 \rightarrow p\mu^-) < 2.6 \times 10^{-9}$ at 90% C.L.



Observed Limit:
 $B(B_s^0 \rightarrow p\mu^-) < 1.2 \times 10^{-8}$ at 90% C.L.

Conclusion

Lepton Flavour Violation

- | Based on 9 fb^{-1} of data collected in 2011-2012 (Run 1) and 2015-2018 (Run 2) LHCb has put ...
- | ... the most stringent limit on

$$B(B_d^0 \rightarrow K^0 \mu^+ e^-) < 5.7 \cdot 10^{-9} \text{ at 90\% C.L.}$$

$$B(B_d^0 \rightarrow K^0 \mu e^+) < 6.8 \cdot 10^{-9} \text{ at 90\% C.L.}$$

$$B(B_d^0 \rightarrow K^0 \mu e) < 10.1 \cdot 10^{-9} \text{ at 90\% C.L.}$$

- | ... the first limit on

$$B(B_s^0 \rightarrow \phi \mu e) < 16.0 \cdot 10^{-9} \text{ at 90\% C.L.}$$

$$B(B_d^0 \rightarrow K^0 \tau^+ \mu^-) < 1.0 \cdot 10^{-5} \text{ at 90\% C.L.} \quad [\text{Preliminary}]$$

$$B(B_d^0 \rightarrow K^0 \tau \mu^+) < 8.2 \cdot 10^{-6} \text{ at 90\% C.L.} \quad [\text{Preliminary}]$$

Baryon and Lepton Number Violation

- | ... the first limit on

$$B(B_d^0 \rightarrow p \mu) < 2.6 \cdot 10^{-9} \text{ at 90\% C.L.} \quad [\text{Preliminary}]$$

$$B(B_s^0 \rightarrow p \mu) < 1.2 \cdot 10^{-8} \text{ at 90\% C.L.} \quad [\text{Preliminary}]$$