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

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On behalf of the LHCb Collaboration

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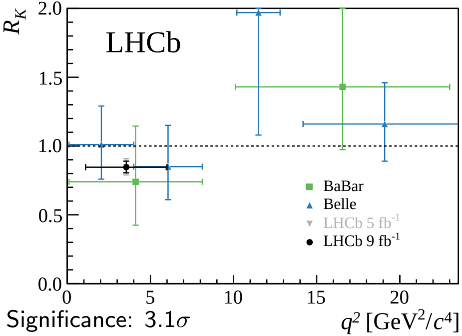
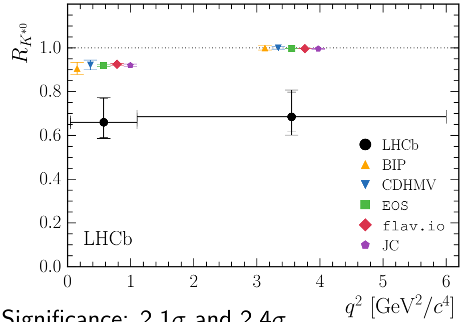
- Test of Lepton Flavour Universality

$$R_K = \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{\mathrm{d}}{\mathrm{d}q^2}\mathcal{B}(B^+ \to K^+\mu^+\mu^-)\mathrm{d}q^2}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \frac{\mathrm{d}}{\mathrm{d}q^2}\mathcal{B}(B^+ \to K^+e^+e^-)\mathrm{d}q^2} \xrightarrow{\text{SM}} 1$$

LHCb-PAPER-2021-004

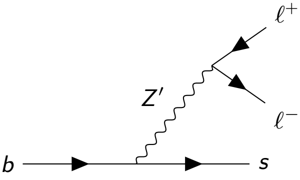


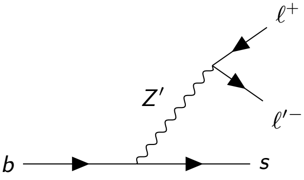
LHCb-PAPER-2017-013



- Significance: 3.1σ
- Significance: 2.1σ and 2.4σ

Lepton Flavour Universality Violation $\Longleftrightarrow$ Lepton Flavour Violation





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

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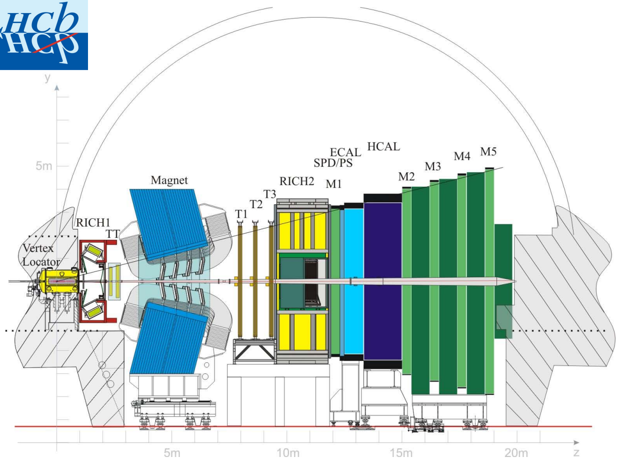


Extensive Physics Programme

- 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: $2 < \eta < 5$

Lepton Flavour Violation

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

Lepton Number Violation

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

Recent Results from LHCb

Lepton Flavour Violation

1. Search for $B_d^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$ — LHCb-PAPER-2022-008
2. Search for $B_d^0 \to K^{*0}\tau^\pm\mu^\mp$ — to appear in LHCb-PAPER-2022-021

Baryon and Lepton Number Violation

3. Search for $B_d^0 \to p\mu^-$ and $B_s^0 \to p\mu^-$ — to appear in LHCb-PAPER-2022-022

Branching Fraction Measurements at LHCb

- Measure relative to known B meson decay

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

- Each search involves the same steps:

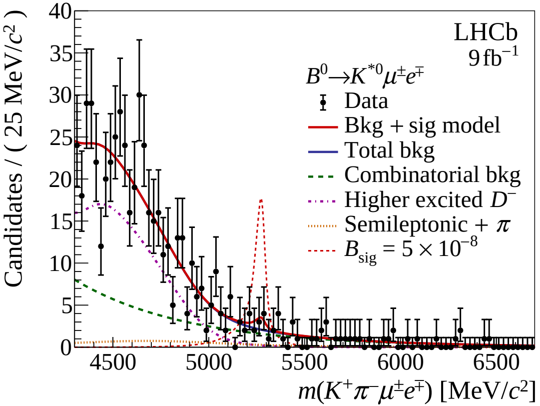
1. Event selection + fit to data $\Rightarrow$ Number of signal events N_{sig}
2. Separate analysis of normalisation mode $\Rightarrow$ Number of events N_{norm}
3. Selection efficiencies and systematic uncertainties $\Rightarrow$ Ratio of efficiencies $\epsilon_{\text{norm}}/\epsilon_{\text{sig}}$
4.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

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

Search for $B_d^0 \to K^{*0}\mu^\pm e^\mp$ and $B_s^0 \to \phi\mu^\pm e^\mp$

Main Backgrounds

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



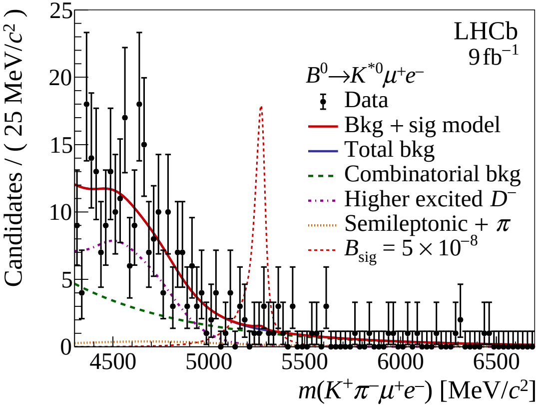
Fit Model

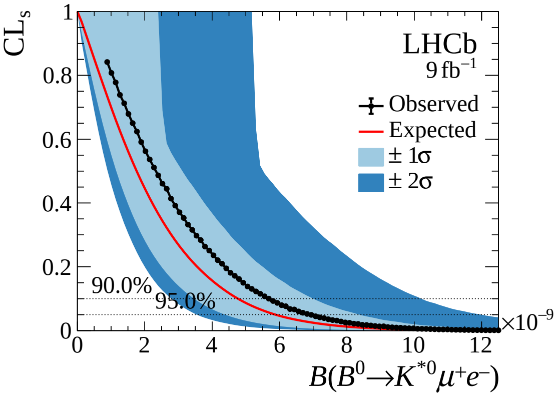
- Signal: Sum of 2 Crystal Ball functions
  - Shape parameters taken from simulation
  - Mass resolution corrected using $B_d^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}$ and $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi$
- Partially reconstructed Bkgs: Model with KDE based on simulation
- Combinatorial Bkg: Single exponential
- 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 $\Rightarrow$ Set an upper limit

Main Systematic Uncertainties

1. Branching fraction of normalisation mode
   - For $B_d^0 \to K^{*0}\mu^\pm e^\mp$ this is $B_d^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}$: Effect is 4.0%
   - For $B_s^0 \to \phi\mu^\pm e^\mp$ this is $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi$: Effect is 4.8%
   - These are also potential backgrounds and are explicitly vetoed in the selection of signal candidates
2. Decay time distribution of $B_s^0 \to \phi\mu^\pm e^\mp$
   - Because B_s meson decay width difference $\Delta\Gamma_s \neq 0$
   - Heavy and light mass eigenstates have difference 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 $B_d^0 \to K^{*0}\mu^\pm e^\mp$: 5.2% to 6.7% (depending on data taking period)
   - For $B_s^0 \to \phi\mu^\pm e^\mp$: 6.9% to 8.5% (depending on data taking period)

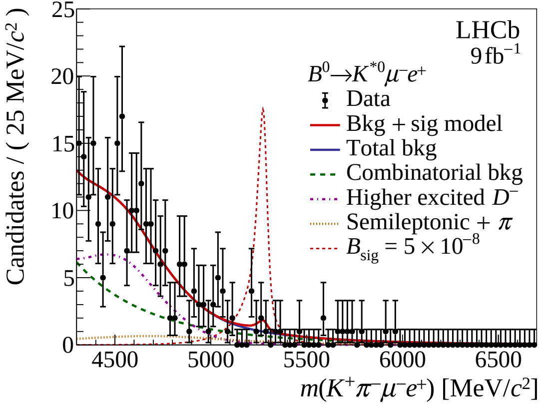
Limit on $B_d^0 \to K^{*0}\mu^+e^-$

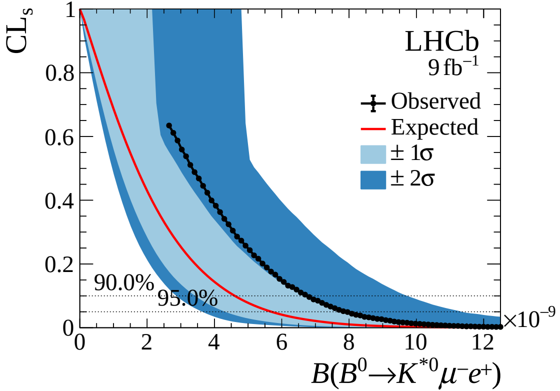




- Observed Limit:
  $\mathcal{B}(B_d^0 \to K^{*0}\mu^+e^-) < 5.7 \times 10^{-9}$ at 90% C.L.
- Expected Limit:
  $\mathcal{B}(B_d^0 \to K^{*0}\mu^+e^-) < 4.8 \times 10^{-9}$ at 90% C.L.

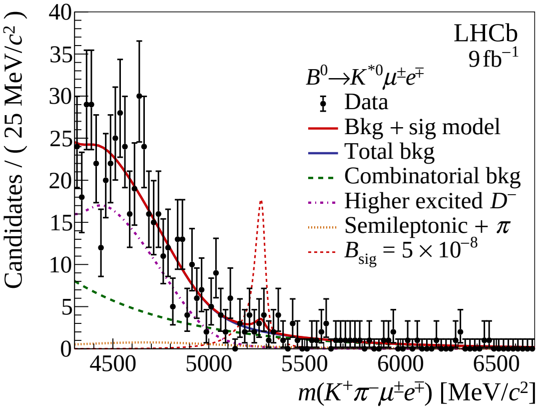
Limit on $B_d^0 \to K^{*0}\mu^- e^+$

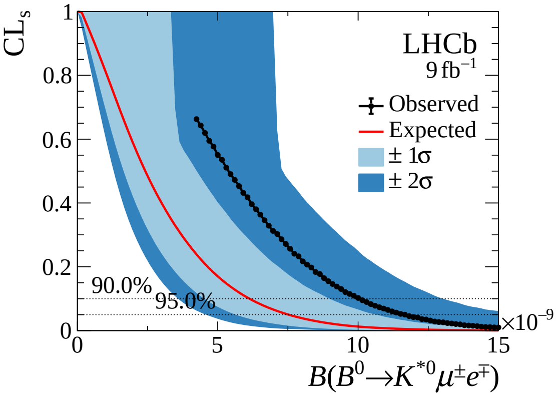




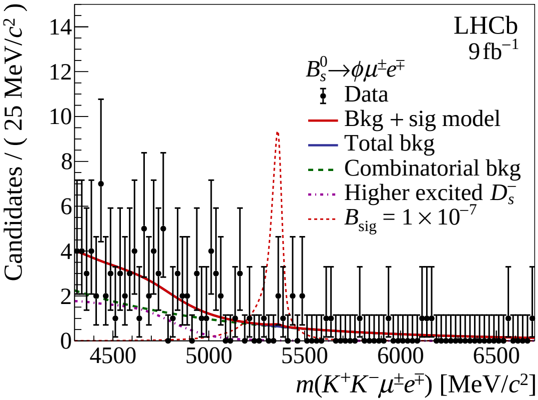
- Observed Limit:
  $\mathcal{B}(B_d^0 \to K^{*0}\mu^- e^+) < 6.8 \times 10^{-9}$ at 90% C.L.
- Expected Limit:
  $\mathcal{B}(B_d^0 \to K^{*0}\mu^- e^+) < 4.6 \times 10^{-9}$ at 90% C.L.

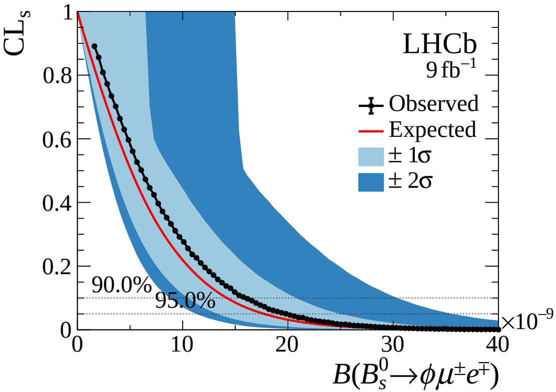
Limit on $B_d^0 \to K^{*0}\mu^\pm e^\mp$





- Observed Limit:
  $\mathcal{B}(B_d^0 \to K^{*0}\mu^\pm e^\mp) < 10.1 \times 10^{-9}$ at 90% C.L.
- Expected Limit:
  $\mathcal{B}(B_d^0 \to K^{*0}\mu^\pm e^\mp) < 6.1 \times 10^{-9}$ at 90% C.L.





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

Search for $B_d^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$

Event Reconstruction

τ Lepton

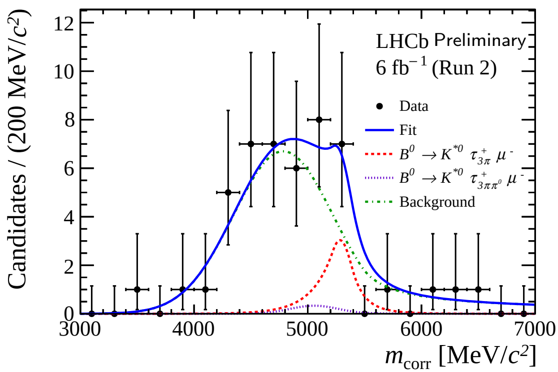
- τ lepton is short-lived and decays before reaching the detector
- Only reconstruct $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ and $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$
- Introduces additional challenges:
  1. Loss of statistics: selected τ decays have a combined branching fraction of only 14%
  2. Neutrinos 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

$$m_{\text{corr}} \equiv \sqrt{p_\perp^2 + m_{K^*\tau\mu}^2} + p_\perp$$

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

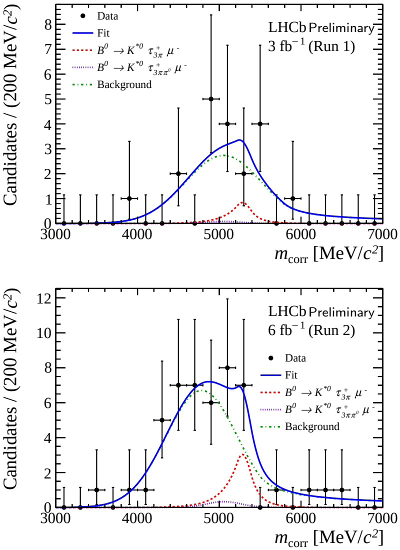


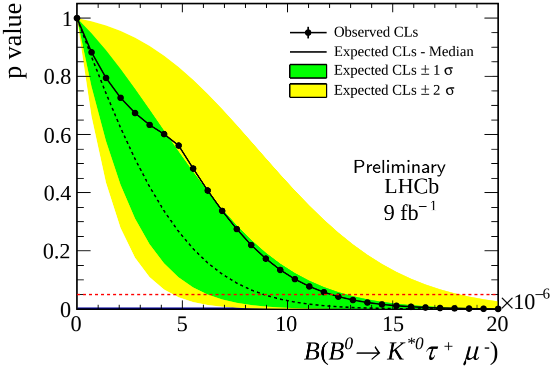
Fit Model

- Signals: double-sided Crystal Ball function
  - Shape parameters taken from simulation
- Background: double-sided Crystal Ball function
  - Main sources:
    For $B_d^0 \to K^{*0}\tau^-\mu^+$: $B_d^0 \to D^{*-}\mu^+\nu_\mu$
    For $B_d^0 \to K^{*0}\tau^+\mu^-$: $B_d^0 \to D^{*-}\tau^+\nu_\tau$
  - 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
- $B_d^0 \to K^{*0}\tau^+\mu^-$ and $B_d^0 \to K^{*0}\tau^-\mu^+$ are fitted independently
- No excess found $\Rightarrow$ Set an upper limit

Main Systematic Uncertainties

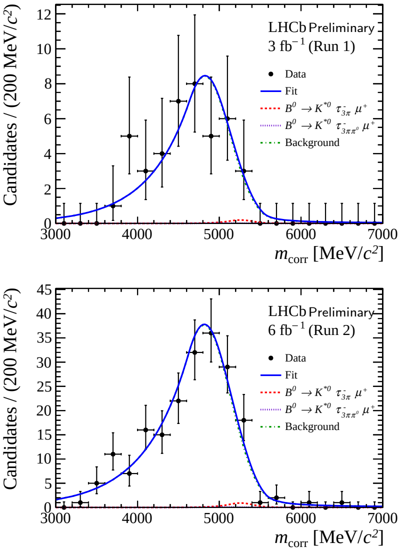
1. Choice of control region for background modelling
   - Select control region by relaxing the MVA requirement that suppresses combinatorial background
   - Signal contamination for $\mathcal{B}(B_d^0 \to K^{*0}\tau^\pm\mu^\mp) = 10^{-5}$ is $< 5\%$
   - Background shape parameters varied using alternative control regions
   - This impacts limit by 18% to 26%
2. Branching fraction of normalisation Mode
   - $B_d^0 \to D^- D_s^+$ with $D^- \to K^+\pi^-\pi^-$ and $D_s^+ \to K^+K^-\pi^+$
   - Increases limit by 3% to 4%

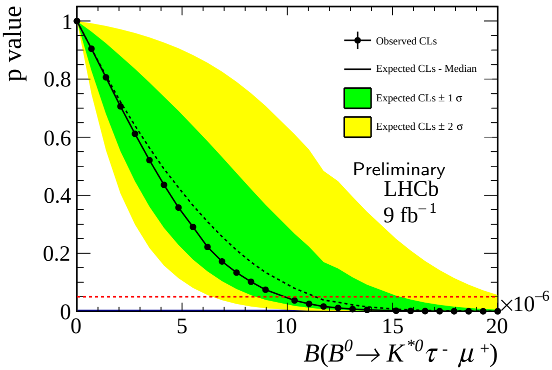




- Observed Limit:
  $\mathcal{B}(B_d^0 \to K^{*0}\tau^+\mu^-) < 1.0 \times 10^{-5}$ at 90% C.L.

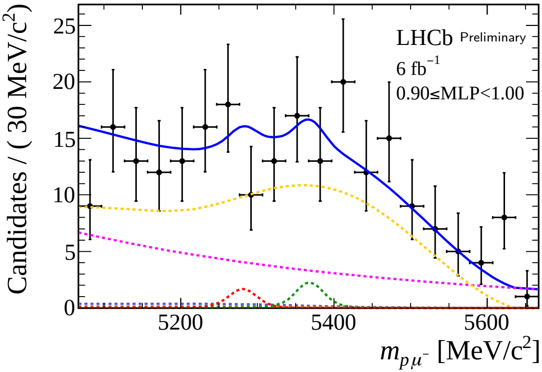
Limit on $B_d^0 \to K^{*0}\tau^-\mu^+$





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

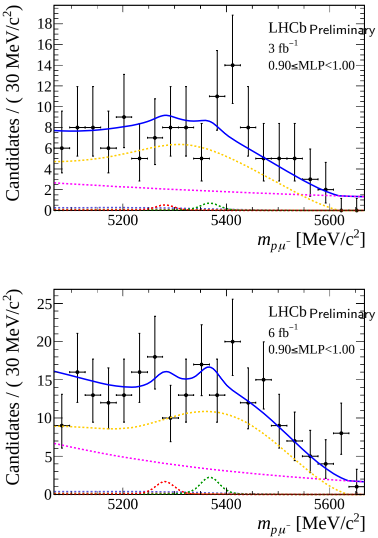
Search for $B_d^0 \to p\mu^-$ and $B_s^0 \to p\mu^-$

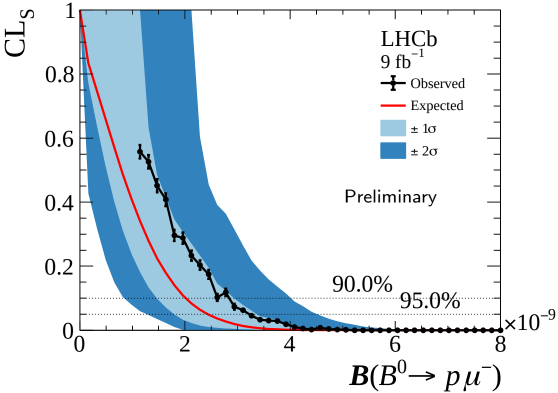


Fit Model

- Signals:
  double-sided Crystal Ball function + Gaussian
- Physics Bkg:
  - Shapes taken from simulation
  - Primarily: $\Lambda_b \to p\mu^-\bar{\nu}_\mu$
  - Additional minor contributions:
    $B_d^0 \to \pi^-\mu^+\nu_\mu$ and $B_s^0 \to K^-\mu^+\nu_\mu$
- 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

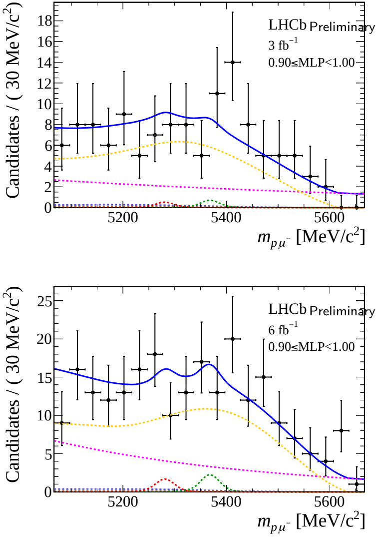
Limit on $B_d^0 \to p\mu^-$

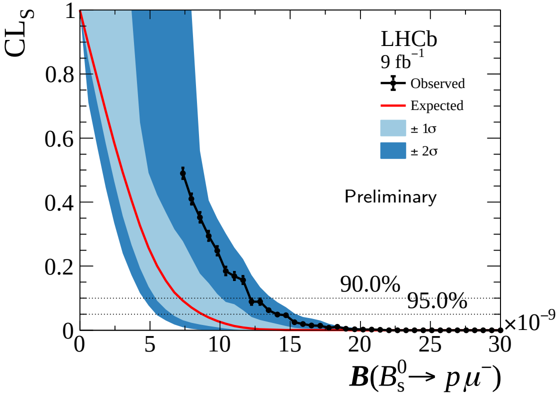




- Observed Limit:
  $\mathcal{B}(B_d^0 \to p\mu^-) < 2.6 \times 10^{-9}$ at 90% C.L.

Limit on $B_s^0 \to p\mu^-$





- Observed Limit:
  $\mathcal{B}(B_s^0 \to p\mu^-) < 1.2 \times 10^{-8}$ 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

$$\mathcal{B}(B_d^0 \to K^{*0}\mu^+e^-) < 5.7 \times 10^{-9} \text{ at 90\% C.L.}$$
$$\mathcal{B}(B_d^0 \to K^{*0}\mu^-e^+) < 6.8 \times 10^{-9} \text{ at 90\% C.L.}$$
$$\mathcal{B}(B_d^0 \to K^{*0}\mu^\pm e^\mp) < 10.1 \times 10^{-9} \text{ at 90\% C.L.}$$

- ... the first limit on

$$\mathcal{B}(B_s^0 \to \phi\mu^\pm e^\mp) < 16.0 \times 10^{-9} \text{ at 90\% C.L.}$$
$$\mathcal{B}(B_d^0 \to K^{*0}\tau^+\mu^-) < 1.0 \times 10^{-5} \text{ at 90\% C.L.} \quad \text{[Preliminary]}$$
$$\mathcal{B}(B_d^0 \to K^{*0}\tau^-\mu^+) < 8.2 \times 10^{-6} \text{ at 90\% C.L.} \quad \text{[Preliminary]}$$

Baryon and Lepton Number Violation

- ... the first limit on

$$\mathcal{B}(B_d^0 \to p\mu^-) < 2.6 \times 10^{-9} \text{ at 90\% C.L.} \quad \text{[Preliminary]}$$
$$\mathcal{B}(B_s^0 \to p\mu^-) < 1.2 \times 10^{-8} \text{ at 90\% C.L.} \quad \text{[Preliminary]}$$