Lepton universality, flavor and number violation in B and τ decays at LHCb

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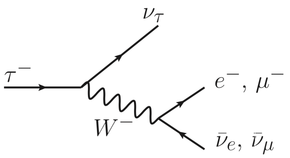
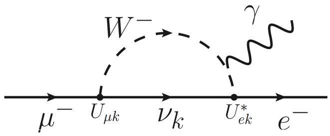
Introduction

- In the Standard Model, couplings of the gauge bosons to leptons are independent of lepton flavour
  $\rightarrow$ branching fractions of e, μ and τ differ only by phase space and helicity-suppressed contributions

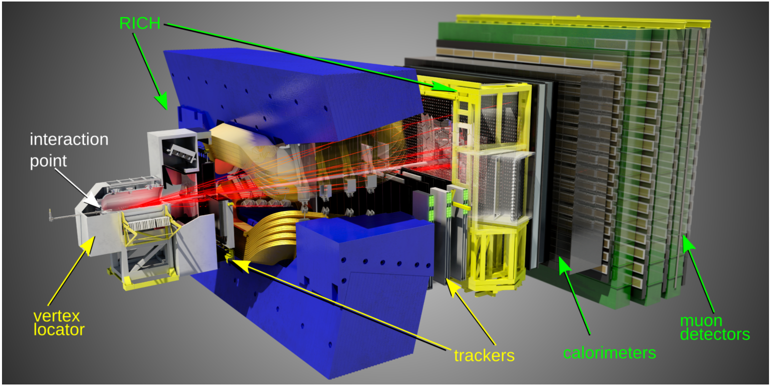
- Lepton flavour violation has only been observed in neutrino oscillations
  $\rightarrow$ all charged LFV amplitudes are strongly suppressed

- Any sign of lepton flavour violation or lepton flavour non-universality would be a direct sign for new physics





The LHCb detector



- Forward arm spectrometer to study b- and c-hadron decays $(2 < \eta < 5)$
  - Good vertex and impact parameter resolution $(\sigma(IP) = 15 + 29/pT)m)$
  - Excellent momentum resolution $(\sigma(m_B) \sim 25\,\mathrm{MeV}/c^2$ for 2-body decays)
  - Excellent particle ID (μ ID 97% for $(\pi \to \mu)$ misID of 1-3%)
  - Versatile & efficient trigger

[JINST 3 (2008) S080005]

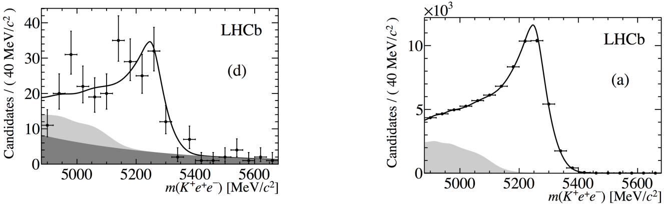
LFU in $B^+ \to K^+ l^+ l^-$

LHCb, PRL 113 (2014) 151601

$$R(K)^{SM} = \frac{BR(B^+ \to K^+\mu^+\mu^-)}{BR(B^+ \to K^+e^+e^-)} = 1 \pm \mathcal{O}(10^{-4})$$

[C. Bobeth et al., JHEP 07 (2007) 040]

- FCNC process, only ocurring at loop level in the SM
- Measured relative to $B^+ \to K^+ J/\psi(l^+l^-)$ to cancel experimental systematic associated to differences between electrons and muons



Note: FSR simulated using PHOTOS. Dominant effect to q^2 migration is Bremsstrahlung in the detector.

LFU in $B^+ \to K^+ l^+ l^-$

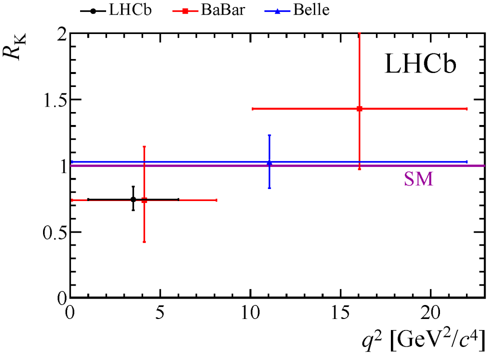
LHCb, PRL 113 (2014) 151601

- Measurement performed with $3\,\text{fb}^{-1}$ of data, in $1 < q^2 < 6\,\text{GeV}/c^2$

$$R_K = 0.745\,^{+0.090}_{-0.074} \pm 0.036$$

Compatible with SM at 2.6σ

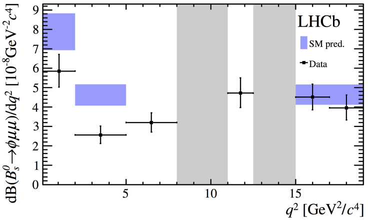
$\to$ Consistent with $b \to s\mu\mu$ anomalies, if NP couples only to muons and not electrons



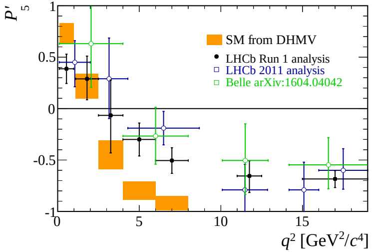
$\to$ Clear motivation to explore related LFU ratios ($R_{K^{*0}}$, R_ϕ, ...)

Anomalies in $b \to s\mu^+\mu^-$ transitions

- Branching fractions of $B \to K^{(*)}\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$ and $\Lambda_b \to \Lambda\mu^+\mu^-$ (1σ to 3σ depending on final state)
- Angular analyses of $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$ and $B^0 \to K^{*0}\mu^+\mu^-$ ($\sim 3\sigma$)
- Lepton flavour universality in $B^+ \to K^+ l^+ l^-$ (2.6σ)



LHCb, JHEP09(2015)179



LHCb, JHEP 02 (2016) 104

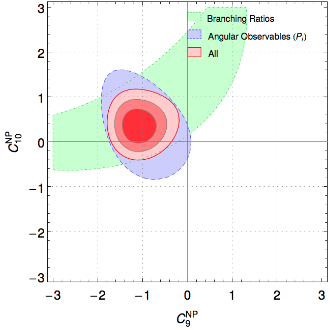
See F. Polci's talk yesterday (WG3)

Global fits to $b \to s\mu^+\mu^-$ observables

Model independent approach

$$\mathcal{H}^{\text{eff}} \sim \sum_i (C_i^{SM} + \Delta C_i^{NP})\mathcal{O}_i$$

where heavy fields are integrated out and *Wilson coefficients* (C_i) and *operators* ($\mathcal{O}_i$) encode coupling strength and Lorentz structure



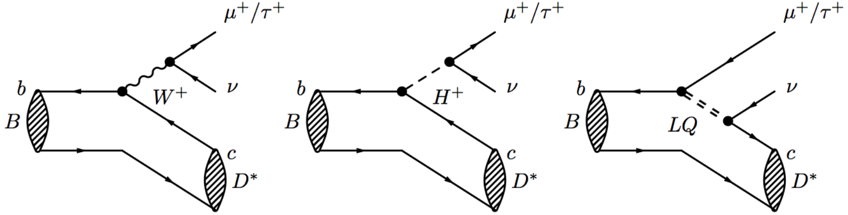
[Descotes-Genon et al, 1510.04239v3]

→ Angular observables, BR's and R_K are compatible with a modified vector coupling $C_9^{\mu\mu} = -1$ and $\Delta C_9^{ee} = 0$

→ Best fit $\sim 4\sigma$ from the SM prediction

→ **LFU ratios free from QCD uncertainties that may affect other observables**

LFU in $B^0 \to D^{*-} l^+ \nu_l$

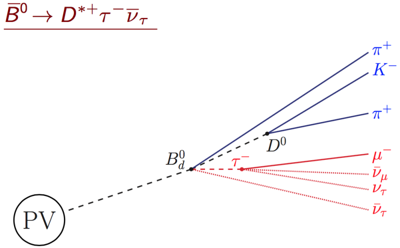


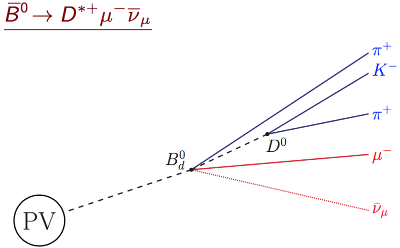
- In the SM the only difference between the two decays is the mass of the lepton
- Theoretically clean

$$R(D^*)^{SM} = \frac{BR(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{BR(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} = 0.252 \pm 0.003$$

[S.Fajfer et al., PRD85 (2012) 094025]

Experimental challenge





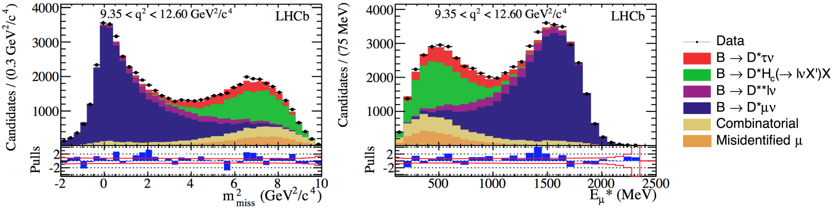
- Missing neutrinos $\Rightarrow$ No narrow peak to fit (in any distribution)
  - Calculate m^2_{missing}, q^2 and E_μ in approximate rest frame
- Main backgrounds are partially reconstructed B decays
  - $B \to D^*\mu\nu$, $B \to D^{**}\mu\nu$, $B \to D^* D(\mu X)X$ ...
- Isolation MVA used to reject physics backgrounds with additional cuts and to select control samples of specific backgrounds

See C. Bozzi's talk on Thursday (WG2)

Result

LHCb, PRL 115 (2015) 111803

- Three dimensional template fit ($m^2_{missing}$, E_μ, q^2 shown)
  - Large MC samples for signal and physics backgrounds (data-driven syst.)
  - Background from μ misID and combinatorial from data
- Shape and form factor dependence systematics included in the fit



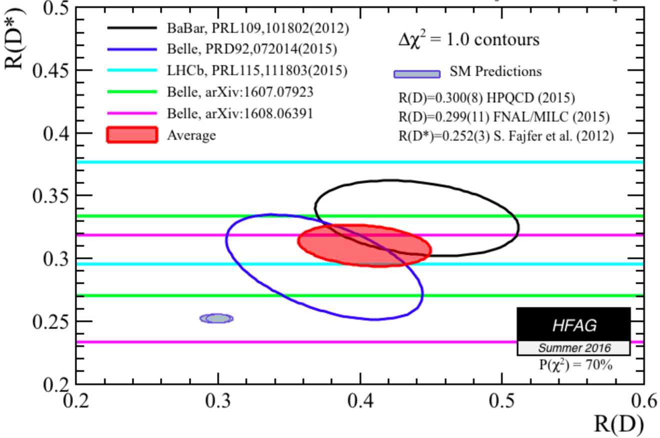
The obtained result

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030$$

is consistent with the SM at 2.1σ level

$R(D^{(*)})$ status

[M. Rotondo]



→ Latest HFAG average: 3.9σ from SM expectation (includes new result from Belle with $\tau \to \pi^+(\pi^0)\nu$)

Search for $B \to \tau^+\tau^-$

LHCb-CONF-2016-01

- In the SM, difference between $B^0_{(s)} \to \mu\mu$ and $B^0_{(s)} \to \tau\tau$ comes through helicity suppression (lepton mass)
- Clean observables in the SM

[C. Bobeth et al., PRL 96 (2006) 241802]

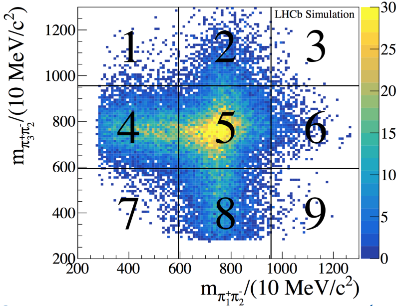
$$\mathcal{B}(B^0 \to \tau\tau)^{SM} = (2.22 \pm 0.19) \times 10^{-8}$$
$$\mathcal{B}(B^0_s \to \tau\tau)^{SM} = (7.73 \pm 0.49) \times 10^{-7}$$

LHCb search

- Fully hadronic τ decays, assumed dominated by

$$\tau \to a_1^-(\rho^0\pi^-)\nu_\tau \to \pi^+\pi^-\pi^-\nu_\tau$$

- Fit to a multivariate clasifier containing kinematic and topological information



See M. Rama's talk on thursday (WG3)

Search for $B \to \tau^+\tau^-$

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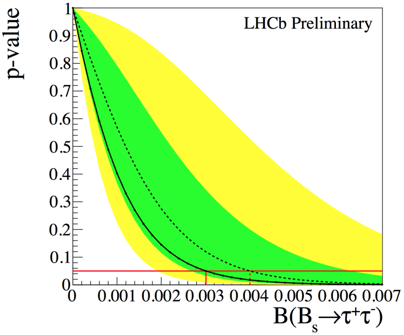
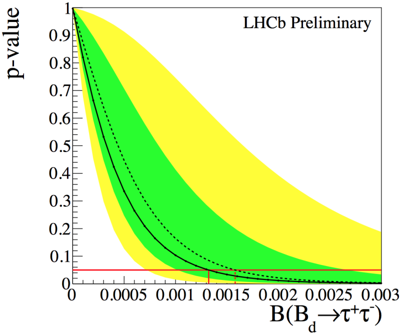




No signal is found, the obtained limits are

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 3.0 \times 10^{-3} \,@\, 95\%\,\mathrm{CL}$$

$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 1.3 \times 10^{-3} \,@\, 95\%\,\mathrm{CL}$$

→ Model-dependent result based on EvtGen simulation of τ decay

Search for $B^0 \to e^\pm\mu^\mp$

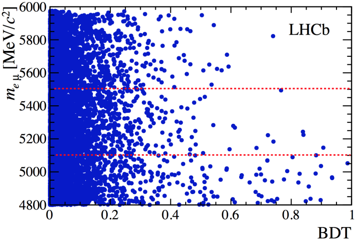
LHCb, PRL 108 (2012) 231801

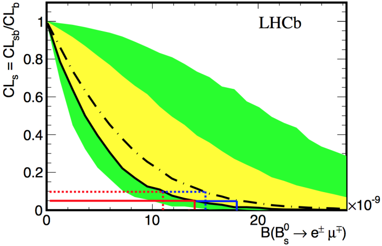
- Search with $1\,\text{fb}^{-1}$ of $7\,\text{TeV}$ data
  - Combined search for B_s^0 and B^0
  - Search invariant mass in bins of BDT
- No signal observed over background expectations
- Limits @ 90% CL

$$\mathcal{B}(B_s^0 \to e^+\mu^-) < 1.1 \times 10^{-9}$$

$$\mathcal{B}(B^0 \to e^+\mu^-) < 2.8 \times 10^{-9}$$

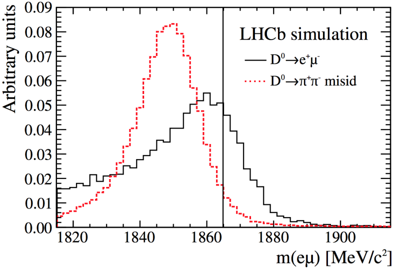
$\times 20$ improvement with respect to previous measurements

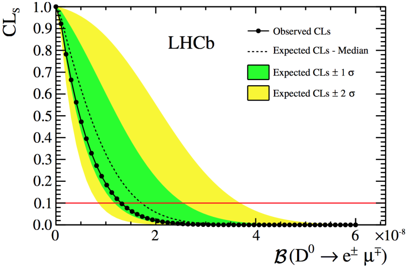




Search for $D^0 \to e^\pm\mu^\mp$

LHCb, PLB 754 (2016) 167





- Search with full Run1 dataset ($3\,\text{fb}^{-1}$)
  - Main background $D^0 \to \pi^+\pi^-$ ($BR \sim 10^{-3}$) rejected using particle ID
  - Using $D^+ \to D^0\pi^+$ decay chain
  - Fit $m(e\mu\pi) - m(e\mu)$ and $m(e\mu)$ in bins of BDT

- No signal is observed and the following limits are set

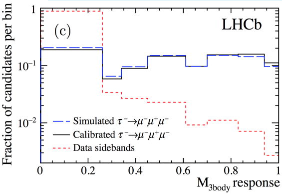
$$\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 1.3(1.6) \times 10^{-8} \text{ @ } 90(95)\% \text{ C.L.}$$

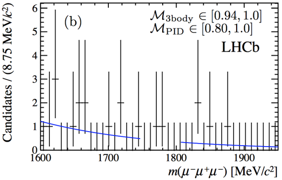
Order of magnitude lower than previous limit [Belle, PRD 81 (2010) 091102]

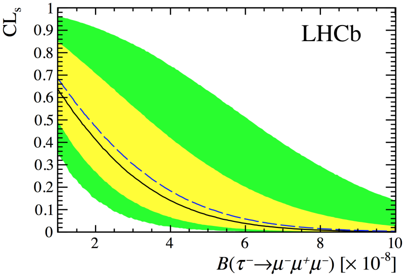
Search for $\tau^+ \to \mu^+\mu^-\mu^+$

LHCb, JHEP 02 (2015) 121

- Full Run1 search, uses classication in 3 dimensions
  - Invariant mass
  - $\mathcal{M}_{\rm 3body}$, to reject multibody decays and combinatorial (vertex quality, flight distance...)
  - $\mathcal{M}_{\rm PID}$, to reject misID background (PID likelihoods)
- Normalising to $D_s^+ \to \phi(\mu^+\mu^-)\pi^+$







Limit set at (90% CL)

$$\mathcal{B}\tau^- \to \mu^-\mu^+\mu^- < 4.6 \times 10^{-8}$$

Compatible with best limit from Belle

[Belle, PLB 687 (2010) 139]

Summary

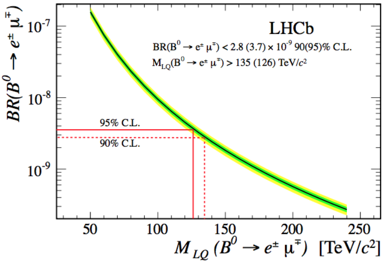
- LFV and LFU are perfect laboratories to search for physics beyond the SM
- Hints of lepton non-universality in $B^+ \to K^+ l^+ l^-$...
  - Compatible with the SM at 2.6σ level
  - Coherent with additional anomalies observed in $b \to s l^+ l^-$ transitions
- ... and in $B^0 \to D^{*+} l^- \nu$ have been measured at LHCb
  - Compatible with the SM at 2.1σ level (3.9σ combination)
  - First measurement of an $R(X_c)$ ratio at a hadron collider
- No signs of LFV in B, D or τ decays have been observed
- Updates of many of these measuremens and LFV and LFU tests of related modes foreseen at LHCb

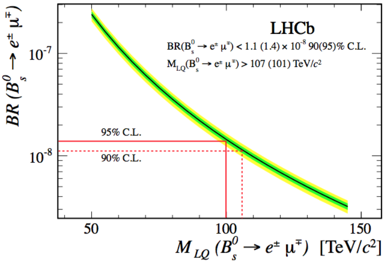
Backup

$B^0_{(s)} \to e^{\pm}\mu^{\mp}$ in Pati-Salam model

UL on branching fractions set lower bounds to the Pati-Salam lepto-quark mass.

(theoretical formula here: Phys. Rev. D 50 (1994) 6843)





- CDF measurements:
  $m_{LQ}(B_s \to e^+\mu^-) > 47.8(44.9)\ TeV/c^2$ @ 90(95)%CL,
  $m_{LQ}(B_d \to e^+\mu^-) > 59.3(56.3)\ TeV/c^2$ @ 90(95)%CL
- LHCb new constraints:
  $m_{LQ}(B_s \to e^+\mu^-) > 107(101)\ TeV/c^2$ @ 90(95)%CL,
  $m_{LQ}(B_d \to e^+\mu^-) > 135(126)\ TeV/c^2$ @ 90(95)%CL