Search for the Lepton Flavour Violating decays $B^0 \to e^\pm\mu^\mp$ and $B_s^0 \to e^\pm\mu^\mp$ with LHCb Run 2 data

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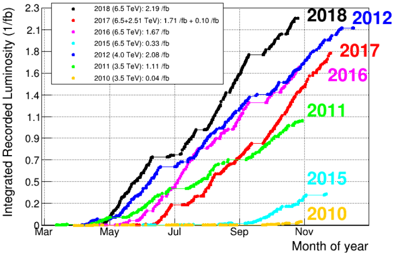
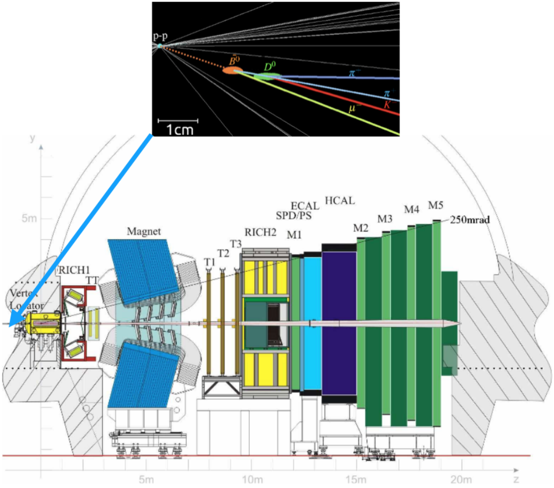
The LHCb experiment

- **Asymmetric forward spectrometer ($2 < \eta < 5$)**
  $\rightarrow$ designed for b and c physics
- excellent vertex, mass and momentum resolution
- very good particle identification
- recorded integrated luminosity:
  $\rightarrow$ Run 1: 3.23 fb^{-1}
  $\rightarrow$ Run 2: 5.85 fb^{-1}



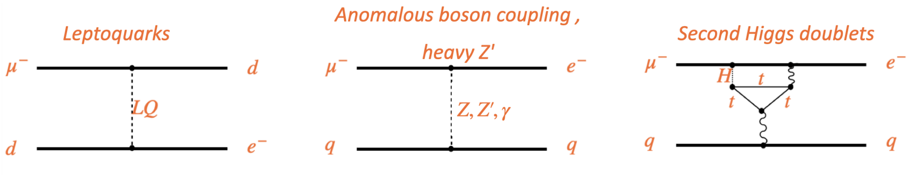


Search for Lepton Flavour Violating decays

- **Lepton flavour violation (LFV)**
  $\rightarrow$ observation of neutrino oscillations implies LFV
  $\rightarrow$ not observed in the charged lepton sector

- [1] D. Bečirević et al, Phys. Rev. D 94, 115021
- [2] I.de Medeiros Varzieles et al, JHEP 06 (2015) 072
- [3] A. Crivellin et al, Phys.Rev.D 92 (2015) 5, 054013
- [4] R.A. Diaz et al, Eur.Phys.J.C 46 (2006) 403-405

- **Search for forbidden b-hadron decays in the SM (e.g. $\rightarrow e\mu, \rightarrow \tau\mu, \rightarrow e\tau$)**
  $\rightarrow$ Standard Model branching fraction is $< 10^{-50}$
  $\rightarrow$ can be enhanced by new mediating particles up to 10^{-11}
  $\rightarrow$ several theoretical models predict LFV (leptoquraks , new gauge boson Z', Higgs doublets) [1,2,3,4]



Links to Lepton Flavour Universality

- **Lepton flavour universality (LFU)**
  $\rightarrow$ scenarios opened by recent hints of LFU anomalies [1,2,3]

  $\rightarrow$ links in some models between LFU and LFV [4,5]

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}$$

$$\mathcal{B} \to K\mu^{\pm}e^{\mp} \sim 3 \cdot 10^{-8}(\frac{1-R_K}{0.23})^2$$

$$\mathcal{B} \to K(e^{\pm}, \mu^{\pm})\tau^{\mp} \sim 2 \cdot 10^{-8}(\frac{1-R_K}{0.23})^2$$

$$\frac{\mathcal{B}(B_s \to \tau^+(e^-, \mu^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)_{SM}} \sim 4(\frac{1-R_K}{0.23})^2$$

$$\frac{\mathcal{B}(B_s \to \mu^+ e^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)_{SM}} \sim 0.01(\frac{1-R_K}{0.23})^2$$

[1] LHCb collaboration, Phys.Rev.Lett.115, 111803

[2] LHCb collaboration, JHEP 08 (2017) 055

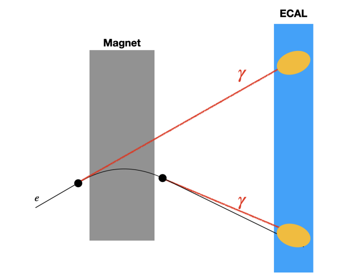
[3] LHCb collaboration, Phys. Rev. Lett. 113, 151601

[4] G. Hiller et al, arXiv: 1609.08895v2

[5] S.L. Glashow et al, Phys. Rev. Lett. 114, 091801

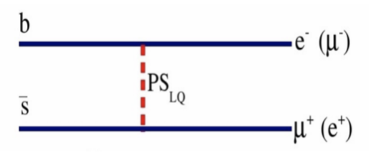
Search for $B^0_{(s)} \to e^{\pm}\mu^{\mp}$

- **Electrons produce bremsstrahlung**
  - $\to$ imperfect bremsstrahlung recovery
  - $\to$ bremsstrahlung categories for $B \to e\mu$: 0γ, 1γ

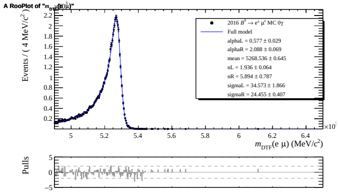


- **Current limits at 90(95) % CL (Run 1)**
  - $\to \mathcal{B}(B_s \to e^{\pm}\mu^{\mp}) < 6.0(7.2) \times 10^{-9}$
  - $\to \mathcal{B}(B \to e^{\pm}\mu^{\mp}) < 0.9(1.2) \times 10^{-9}$
  - LHCb collaboration, JHEP 03 (2018) 078

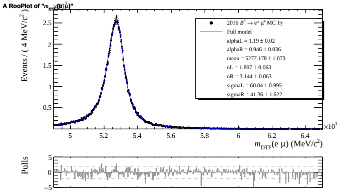
- **Run 2 analysis: 2016 + 2017 + 2018**
  - $\to$ can expect factor $\sim$2 improvement from statistics



without photon recovery



with photon recovery



Analysis strategy

- Measure $\mathcal{B}(B^0_{(s)} \to e^\pm \mu^\mp)$ with respect to B$^+ \to J/\psi(\to \mu^+\mu^-)K^+$

$$\mathcal{B}(B^0_{(s)} \to e^\pm \mu^\mp) = \frac{f_u}{f_{d(s)}} \times \mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+) \times \frac{\mathcal{N}(B^0_{(s)} \to e^\pm \mu^\mp)}{\mathcal{N}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \times \frac{\varepsilon(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\varepsilon(B^0_{(s)} \to e^\pm \mu^\mp)}$$

- Validation of the efficiency corrections checking $r_{J/\psi} = 1$ in bremsstrahlungs categories

$$r_{J/\Psi} = \frac{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} = \frac{\mathcal{N}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\mathcal{N}(B^+ \to J/\psi(\to e^+e^-)K^+)} \times \frac{\varepsilon(B^+ \to J/\psi(\to e^+e^-)K^+)}{\varepsilon(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} = 1$$

Analysis workflow

1. **Selection**
   - Stripping, offline and trigger selection
   - `PID` to remove physics background
   - `MVA` to remove combinatorial background
2. **Determine and correct for selection efficiency**
   - Correct for `tracking`, `PID`, `L0` and B kinematics
   - Use $B^+ \to J/\psi(\mu^+\mu^-)K^+$ and $B^+ \to J/\psi(e^+e^-)K^+$ as control and calibration modes
3. **Determine $\mathcal{B}(B^0 \to e^\pm\mu^\mp)$ and $\mathcal{B}(B^0_s \to e^\pm\mu^\mp)$**
   - Simultaneous fit of the $e\mu$ mass split by years and brem categories
   - Use $B^+ \to J/\psi(\mu^+\mu^-)K^+$ as normalisation channel
4. **Derive the limits for the branching fractions**

Selection

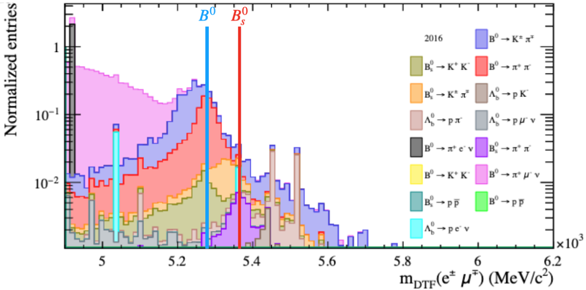
Pre-selection

- use dedicated pre-selection selections for our signal and normalisation channels
- Fiducial cuts, chosen to align with calibration samples acceptance, few examples:
  $\rightarrow p_T(\mu) > 0.8$ GeV, $p_T(e) > 0.5$ GeV, $IP\chi^2(e) > 25$, $p(e,\mu) < 200$ GeV.
- trigger on single electron or signal muon candidate, require good tracks and use decay topology

Particle Identification PID

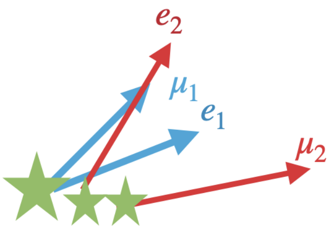
- Criteria to reduce and remove physics background $(e_{\rightarrow K/\pi}, \mu_{\rightarrow K/\pi})$
- Main peaking backgrounds considered: 2-body hadronic decays
  $(B^0_{(s)} \rightarrow h^+h'^-$ with $h^{(\prime)} = \pi, K, p)$
- Also considered: $B^0 \rightarrow \pi\ell\nu$, $\Lambda_b \rightarrow p\ell\nu$, $\Lambda_b \rightarrow pK$ and $\Lambda_b \rightarrow p\pi$
  $\rightarrow e$: `PIDe`> -2 and `MC15TuneV1ProbNNe`> 0.8
  $\rightarrow \mu$: `MC15TuneV1ProbNNmu`> 0.4

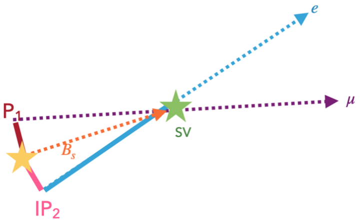
2016

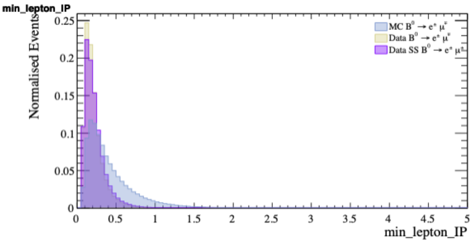


Multivariate Analysis

- Combinatorial background: two tracks associated to a common vertex
- Train a Boosted Decision Tree (BDT) to remove combinatorial background
- Chose discriminating variables that contain information of the topology, vertex quality and track isolation
  $\rightarrow$ e.g. the smallest of the lepton IPs with respect to the PV

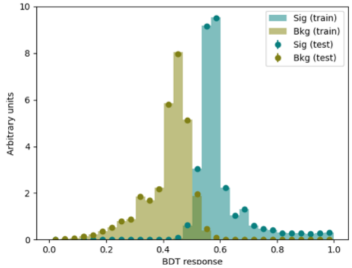


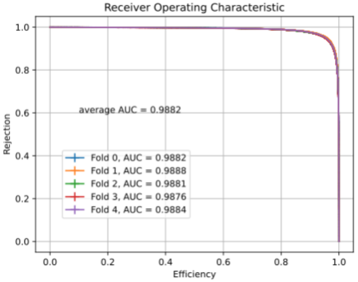




BDT training

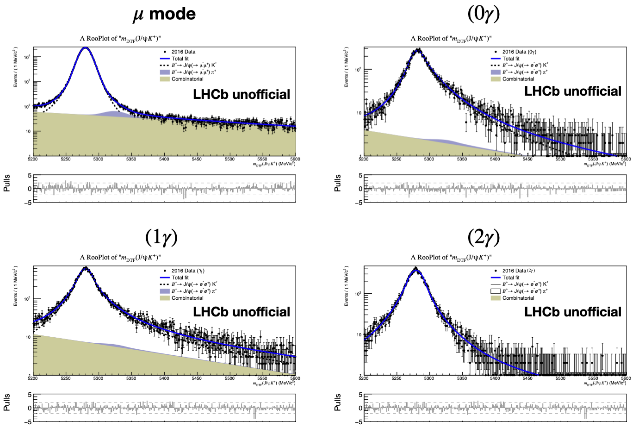
- Signal: efficiency corrected $B^0_{(s)} \to e^{\pm}\mu^{\mp}$ simulation
- Background: sideband data
- Tested different sets of discriminating variables and algorithms
- Use a total of 14 discriminating variables
- Use cross validation (with k=5 folds) for training





Fits to $B^+ \to J/\psi(\to \ell^+\ell^-)K^+$

- Simultaneous fit in 0γ, 1γ and 2γ categories in electron modes and muon mode
  - 1γ: only one electron has brem added
  - 2γ: both electrons has brem added
- Floating $\pi \to K$ mis-ID rate shared between brems and e/μ mode.
- Fits used to validate w_{PID} & w_{L0} corrections measuring $r(J/\psi)$



Corrections

Efficiency corrections

- Selection efficiencies, ε , are taken from simulation
- Well known that the tracking, the PID and the L0 trigger response is badly modeled in simulation
  $\rightarrow$ derive corrections with data driven methods

Kinematic corrections

- Observe discrepancies in the modelling of the B kinematics in simulation
- Train a BDT with the `GBreweighter` package to obtain corrections
- Corrections are obtained from $B^+ \rightarrow J/\psi(\rightarrow \mu^+\mu^-)K^+$ MC and sWeighted data
- Port corrections to $B \rightarrow e^{\pm}\mu^{\mp}$ and $B \rightarrow J/\psi(e^+e^-)K^+$

$\rightarrow$ validate our corrections, by measuring $r_{J/\Psi}$

$r_{J/\psi}$ cross check

- Validate corrections ($w_{TRK} \times w_{PID} \times w_{wL0} \times w_{wBKIN}$)
- Calculate $r_{J/\psi}$ for two bremsstrahlungs categories: 0γ 1γ

$$
\begin{aligned}
r_{J/\psi} &= \frac{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} \\
&= \frac{\mathcal{N}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)}{\mathcal{N}(B^+ \to J/\psi(\to e^+e^-)K^+)} \times \frac{\varepsilon(B^+ \to J/\psi(\to e^+e^-)K^+)}{\varepsilon(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \\
&= 1
\end{aligned}
$$

year	Correction	$r_{J/\psi}(0\gamma)$	$r_{J/\psi}(1\gamma)$
2016	no corrections	1.14	1.29
2016	fully corrected	1.03	1.12
2017	no corrections	1.12	1.21
2017	fully corrected	1.01	1.06
2018	no corrections	1.20	1.31
2018	fully corrected	1.00	1.06

Invariant mass fit

Simultaneous fit of $m_{e\mu}^{DTF}$

- Model:
  - $B^0 \to e^\pm \mu^\mp$: bifurcated DSCB
  - $B_s^0 \to e^\pm \mu^\mp$: bifurcated DSCB
  - Combinatorial: exponential
- Fit 6 datasets: 2 brem categories $\times$ 3 years
- Branching fractions are shared between all categories

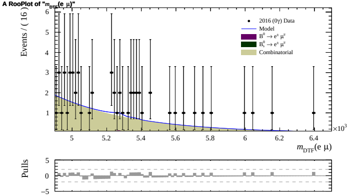
$$\mathcal{N}(B^0_{(s)} \to e^\pm \mu^\mp)_{year,brem} = \frac{f_{d(s)}}{f_u} \times \frac{\varepsilon(B^0_{(s)} \to e^\pm \mu^\mp)_{year,brem}}{\varepsilon(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)_{year}} \times \frac{\mathcal{B}(B^0_{(s)} \to e^\pm \mu^\mp)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \times \mathcal{N}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)_{year}$$

Fit under bkg only hypothesis

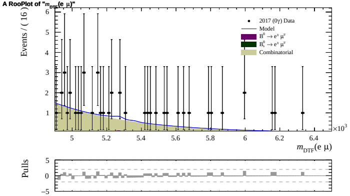
Toys: generate from fits to data sidebands, and extrapolation over full fit range

Fit toy datasets

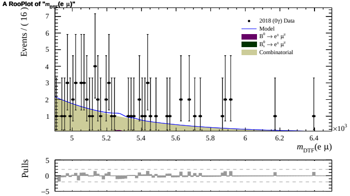
2016, 0γ



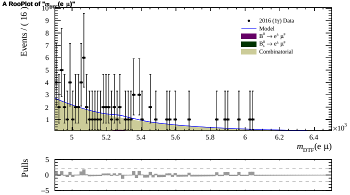
2017, 0γ



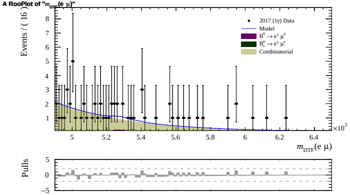
2018, 0γ



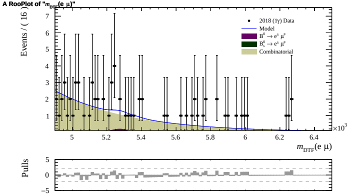
2016, 1γ



2017, 1γ



2018, 1γ



Summary

So far:

- Full selection in place
  - offline, trigger and alignment selection finalised
  - BDT trained and optimised to suppress combinatorial background
- Implemented full correction to simulation (tracking, PID, L0 and B kinematics)
- $r_{J/\Psi}$ determined applying corrections
- Simultaneous fits to data and toy datasets

On-going:

- Sensitivity studies
- Background studies and validation using $B \to hh$ stripping output
- Systematics from ε and mass fits