# Lepton flavour violation and rare decays at LHCb

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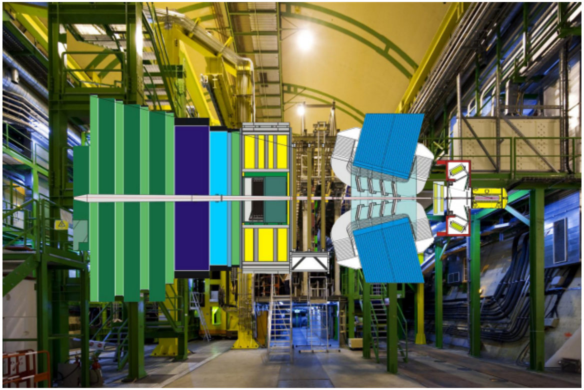
# The LHCb experiment

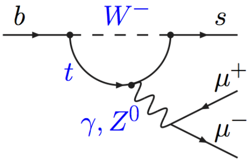
- Single-arm spectrometer covering the forward $2 < \eta < 5$ region
- Dedicated to heavy flavour physics
- Looks for indirect evidence of new physics in CP violation and rare decays

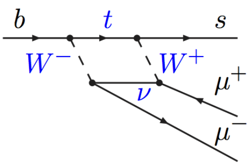
**Momentum resolution:**
$\delta p/p = 0.5$ % at low momentum to $1.0$ % at $200$ GeV/c
**Impact parameter resolution:**
$\sigma_{IP} \sim (15 + 29/p_T\,[\text{GeV}])\ \mu m$
**Primary vertex resolution:**
$13\ \mu m$ in x and y, and $71\ \mu m$ in z
**Decay time resolution:**
$\sigma_\tau \sim 45$ fs
**Excellent particle identification**



Int.J.Mod.Phys.A30,1530022(2015),
JINST3(2008)S08005

- Processes between up-type quarks and down-type quarks can be mediated by electroweak Flavour Changing Neutral Current (FCNC) processes - in the Standard Model (SM)
- These decays are suppressed in the SM, so more sensitive to new physics
- There exist many precise SM predictions
- New particles in the loop level processes could cause large deviations from the SM predictions
- The pattern of deviations can guide towards the physics beyond the SM

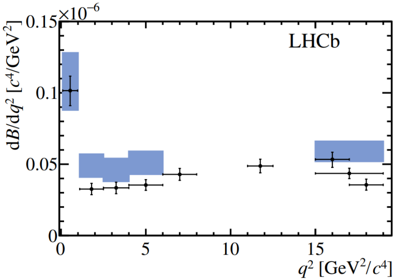


**Anomalies in** $b \to sll$ **transitions:**

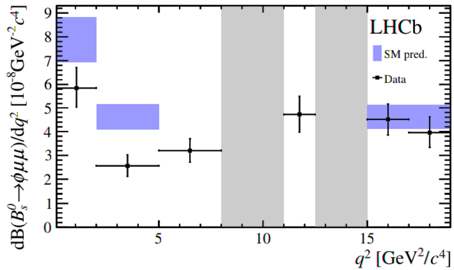
[JHEP04(2017)142]

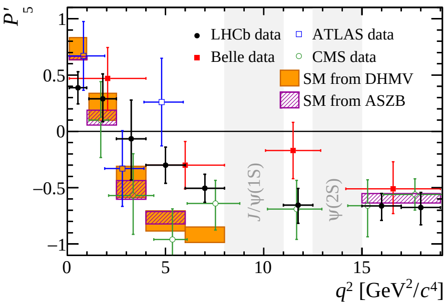
$B^0 \to K^{*0}\mu\mu$




[JHEP09(2015)179]

$B_s^0 \to \phi\mu\mu$




$B^0 \to K^{*0}\mu\mu$

[JHEP02(2016)104]

[PhysRevLett.118.111801]

[arXiv:hep-ex/1710.02846]

[ATLAS-CONF-2017-023]

$\to$ measurements go to the same direction!

**Hints on lepton flavour non-universality**:

PRL 113 (2014) 151601

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst}) \qquad 1.0 < q^2 < 6.0\ \text{GeV}^2/c^4$$

JHEP 08 (2017) 055

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu\mu)}{\mathcal{B}(B^0 \to K^{*0}ee)} = \begin{cases} 0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}) & 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4 \\ 0.069^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst}) & 1.1 < q^2 < 6.0\ \text{GeV}^2/c^4 \end{cases}$$

PRL 115, 111803 (2015)

$$R_{D^*} = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\nu_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\nu_\mu)} = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$$

$$R_K^{exp} < R_K^{SM} \qquad R_{K^*}^{exp} < R_{K^*}^{SM} \qquad R_{D^*}^{exp} > R_{D^*}^{SM}$$

If LUV in the lepton flavour conserving decay channels exists, it may imply the existence of a charged lepton flavour violation [Phys.Let.B (2015) 09 040]

# Chosen decays

This talk:

$B^0_s \to \bar{K}^{*0}\mu\mu$, $B^0{}_{(s)} \to \mu\mu$, $B^0{}_{(s)} \to \tau\tau$

$B^0{}_{(s)} \to e^{\pm}\mu^{\mp}$, + ongoing

$$B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$$

- **Decay searched:** $B_s^0 \to \bar{K}^{*0}(\to K^-\pi^+)\mu^+\mu^-$ - $b \to dll$ FCNC transition, more CKM suppressed compared to $b \to sll$

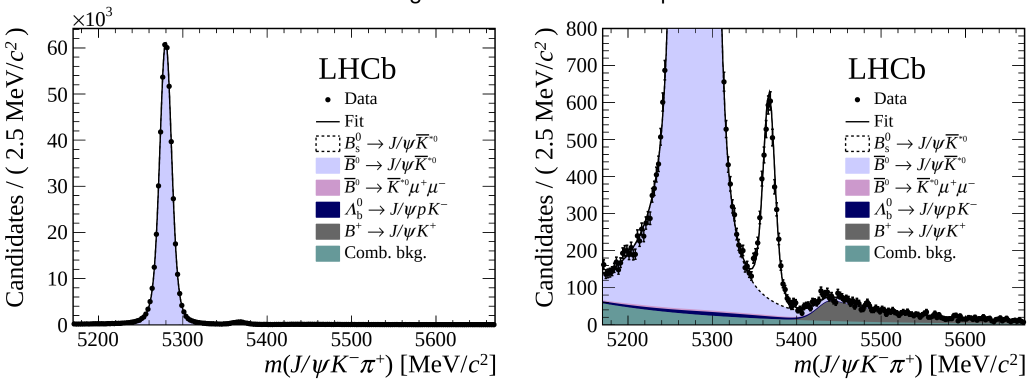
SM predictions [JHEP 08 (2016) 098][PoS LATTICE2014 (2015) 372]:

$$\mathcal{B}_{SM}(B_s^0 \to \bar{K}^{*0}\mu^+\mu^-) \sim \mathcal{O}(10^{-8})$$

Can be used to compute $|V_{td}/V_{ts}|$

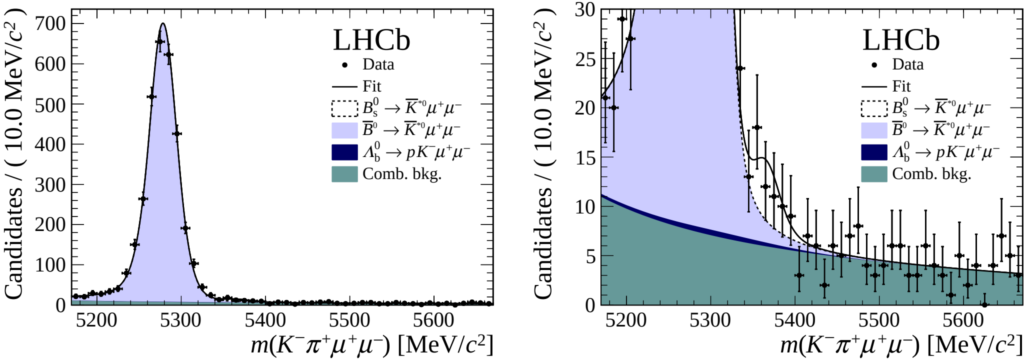
- **Dataset:** $1.0\,\mathrm{fb}^{-1}(7\ \mathrm{TeV}) + 2.0\,\mathrm{fb}^{-1}(8\ \mathrm{TeV}) + 1.6\,\mathrm{fb}^{-1}(13\ \mathrm{TeV})$
- **Normalisation channels:** $B^0 \to J/\psi(\to \mu^+\mu^-)\bar{K}^{*0}(\to K^-\pi^+)$

In the three highest neural network response bins:



- **Background sources:** $\Lambda_b^0 \to pK\mu^+\mu^-$, $B^0 \to K^{*0}\mu^+\mu^-$
- **Fit to invariant mass:** performed in bins of neural network output, $m_{K^-\pi^+}$ within $\pm 70\,\mathrm{MeV/c^2}$ of the $\overline{K}^{*0}$, $0.1 < q^2 < 19.0\ \mathrm{GeV^2/c^4}$ ($q^2 = m^2_{\mu^+\mu^-}$), excluding charmonium resonances

In the three highest neural network response bins:




First evidence ($3.4\ \sigma$)!

$$\mathcal{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-) = (2.9 \pm 0.9 \pm 0.3) \times 10^{-8}$$

$$B^0{}_{(s)} \rightarrow \mu^+\mu^-$$

- **Decays searched:** Golden channel $B_s^0 \to \mu\mu$ and $B^0 \to \mu\mu$ - very rare loop decay, CKM and helicity suppressed

SM predictions [PRL 112 (2014) 10180]:

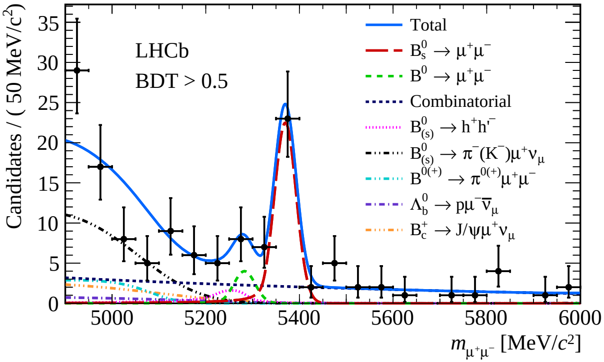
$$\mathcal{B}_{SM}(B_s^0 \to \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}_{SM}(B^0 \to \mu\mu) = (1.06 \pm 0.09) \times 10^{-10}$$

Previous measurement:
from CMS+LHCb 2011+2012 data [Nature 522 (2015) 68]

$$\mathcal{B}(B_s^0 \to \mu\mu) = (2.8 \pm 0.7) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu\mu) = (3.9 \pm 1.6) \times 10^{-10}$$

- **Dataset:** $1.0\,\text{fb}^{-1}(7\text{ TeV}) + 2.0\,\text{fb}^{-1}(8\text{ TeV}) + 1.4\,\text{fb}^{-1}(13\text{ TeV})$
- **Normalisation channels:** $B^0 \to K^+\pi^-$, $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$

- **Background sources:** the dimuon combinatorial events, peaking $B^0_{(s)} \to h^+h'^-, (h, h' = K, \pi)$, $\Lambda^0_b \to p\mu^-\nu$, semileptonic $B^0_{(s)}$
- **Fit 1:** Branching fractions - compatible with SM




First single experiment observation:

$\mathcal{B}(B^0_s \to \mu\mu) = (3.0 \pm 0.7) \times 10^{-9}$ (7.8 $\sigma$ excess)

$\mathcal{B}(B^0 \to \mu\mu) < 3.4 \times 10^{-10}$ @ 95 % CL

**New**: Effective lifetime - complementary to the branching fraction measurement [JHEP05(2017)076]

$$\tau_{\mu^+\mu^-} = \frac{\int_0^\infty t\langle\Gamma(B^0_s\to\mu\mu)\rangle dt}{\int_0^\infty \langle\Gamma(B^0_s\to\mu\mu)\rangle dt}$$

Can be used to extract the mass-eigenstate rate asymmetry

$$\mathcal{A}_{\Delta\Gamma} = \frac{R_H^{\mu^+\mu^-} - R_L^{\mu^+\mu^-}}{R_H^{\mu^+\mu^-} + R_L^{\mu^+\mu^-}},\ \mathcal{A}^{SM}_{\Delta\Gamma} = 1$$

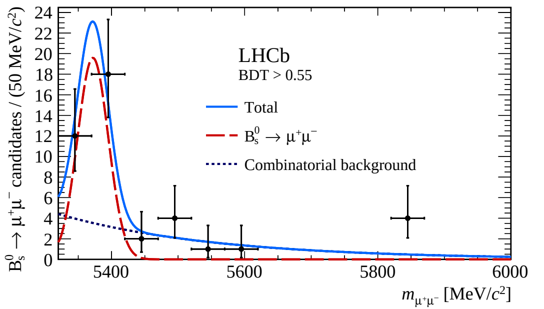
- sensitive to NP: can take values between -1 and +1

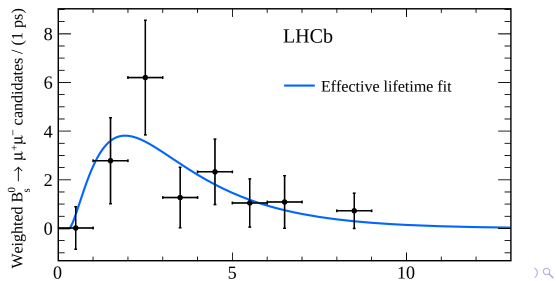
$$\tau(B_s \to \mu\mu) = 2.04 \pm 0.44 \pm 0.05\,\text{ps}$$

consistent with SM @ $1.0\ \sigma$

- proof-of-principle
- will become interesting in the future

- **Fit 2:** Effective lifetime
- looser muon ID requirements
- reduced di-muon mass window
- background-subtracted data (*sPlot*)



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

- **Decay searched:** $B^0_s \to \tau\tau$ and $B^0 \to \tau\tau$

SM predictions [PRL 112 (2014) 101801]:

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

Previous measurements:

$\mathcal{B}(B^0 \to \tau\tau) < 4 \times 10^{-3}$ @ 90% CL [PRL 96 (2006) 241802]

- **Dataset:** $1.0\,\text{fb}^{-1}(7\text{ TeV}) + 2.0\,\text{fb}^{-1}(8\text{ TeV})$
- **Normalisation channels:** $B^0 \to D^-(\to K^+\pi^-\pi^+)\, D_s^+(\to K^-K^+\pi^+)$
- **$\tau$ reconstruction:**

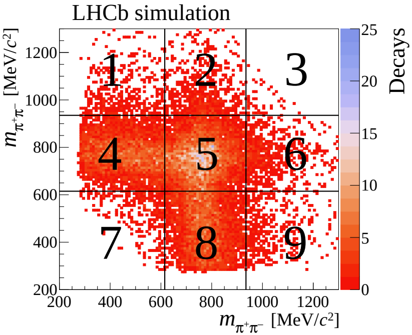
$\tau \to \pi^-\pi^+\pi^-\nu_\tau$ trough $\rho(770)^0$ resonance

- **Region definitions:**

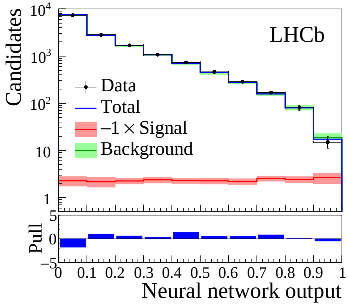
signal - both $\tau$ in 5

control - one $\tau$ in (4,5,8) and the other in (4,8)

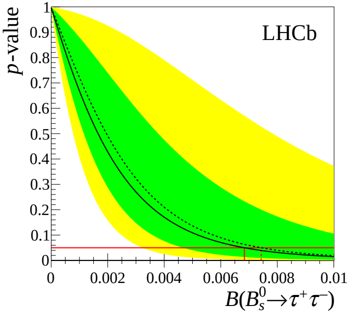
background - at least one $\tau$ in (1,3,7,9)

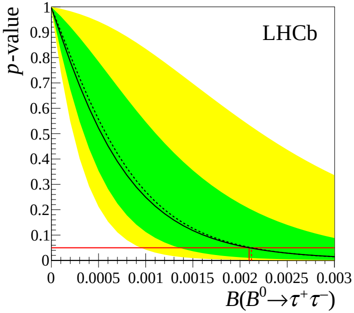


- **Fit to the MVA output:** $m_{\tau\tau}$ gives a weak discrimination, hence the choice of the MVA




$\mathcal{B}(B^0 \to \tau\tau) < 2.1 \times 10^{-3}$ @ 95% CL - world's best limit
$\mathcal{B}(B^0_s \to \tau\tau) < 6.8 \times 10^{-1}$ @ 95% CL - first direct limit

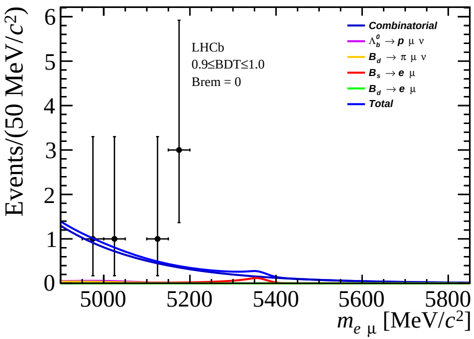


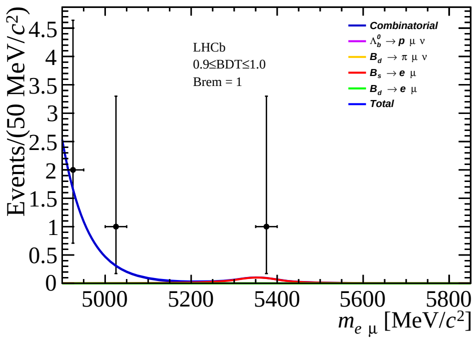



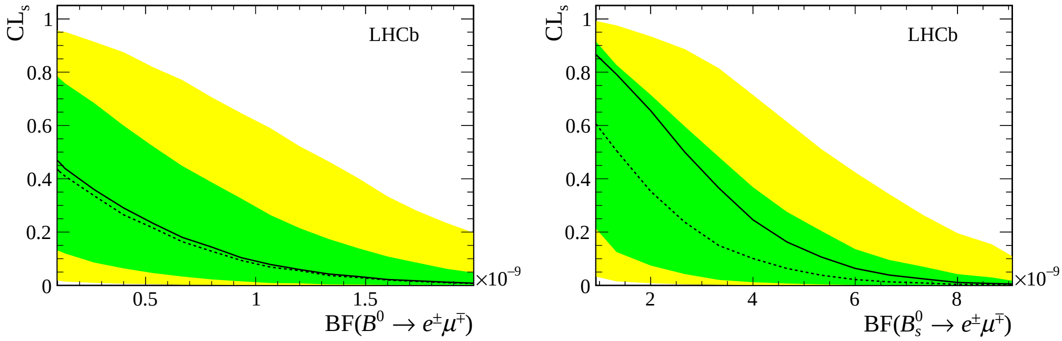
$$B^0{}_{(s)} \to e^{\pm}\mu^{\mp}$$

- **Decays searched:** $B^0 \to e^{\pm}\mu^{\mp}$, $B_s \to e^{\pm}\mu^{\mp}$
- **Dataset:** $1.0\,fb^{-1}(7\,TeV) + 2.0\,fb^{-1}(8\,TeV)$
- **Normalisation channels:** $B^+ \to K^+J/\psi(\to \mu^+\mu^-)$ and $B^0 \to K^+\pi^-$
- **Background sources:** misidentification of $B^0 \to h^+h'^-$ decays, partially reconstructed decays with misidentified particles
- **Fit to invariant mass:** performed, in two bremsstrahlung categories in BDT bins, it showed no excess

BDT most signal-like






$$\mathcal{B}(B^0 \to e^{\pm}\mu^{\mp}) < 1.0\ (1.3) \times 10^{-9}$$
$$\mathcal{B}(B^0_s \to e^{\pm}\mu^{\mp}) < 5.4\ (6.3) \times 10^{-9}$$
@ 90% (95%) CL

# Other analyses

# Other analyses

## $B_s \to \tau\mu$ and $B^0 \to \tau\mu$

It is the first search in the $B_s$ channel.

**Predictions:**

$\mathcal{B}(B_s \to \tau\mu) \sim 10^{-9}$ arXiv:hep-ph/9806359

$\mathcal{B}(B_s \to \tau\mu) \sim 10^{-7}$ arXiv:hep-ph/1504.07928

$\mathcal{B}(B_s \to \tau\mu) \sim 10^{-6}$ arXiv:hep-ph/1211.5168

The experimental upper limit for the $B^0$ channel set by the *BaBar* collaboration:

$\mathcal{B}(B^0 \to \tau\mu) < 2.2 \times 10^{-5}$ at 90 % CL

Phys.Rev.D77:091104,2008

$D^0 \to e^{\pm}\mu^{\mp}$ & more charm

See: talk by J.Brodzicka

$B \to Ke\mu$

The experimental upper limits set by the *BaBar* collaboration:

$$\mathcal{B}(B^+ \to K^+e^+\mu^-) < 9.1 \times 10^{-8}$$
$$\mathcal{B}(B^+ \to K^+e^-\mu^+) < 13 \times 10^{-8}$$

Phys.Rev.D73:092001,2006

**Predictions:**

$$\mathcal{B}(B^+ \to K^+e^+\mu^-) \in [4.2, 6.2] \times 10^{-10}$$

PL B750 (2015) 367

$$\mathcal{B}(B^+ \to K^+e^+\mu^-) \sim 3 \times 10^{-8} \left(\frac{1-R_K}{0.23}\right)^2$$

with $R_K = 0.745$ gives:

$$\mathcal{B}(B^+ \to K^+e^+\mu^-) \sim 3.7 \times 10^{-8}$$

arXiv:hep-ph/1609.08895

# Summary

- Precise measurements of rare decays are a powerful tool to look for new physics
- No observation of the lepton flavour violation in the charged lepton sector
- Any evidence would point directly to new physics
- Results in agreement with the SM $\rightarrow$ set tighter constraints on new physics

**Many other analyses ongoing in LHCb, some will be out soon !**

# Thank you for your attention :)