# $b \to s\ell\ell$ transitions @ LHCb

Julien Cogan, CPPM

4 November 2019, GDR-InF annual workshop

# Outline

1. Introduction

2. Illustration with some recent and on-going LHCb analyses
   - $B^0_{(s)} \to \tau^+\tau^-$
   - $B^0_{(s)} \to \tau^\pm\mu^\mp$
   - $B^0 \to K^{*0}\tau^\mp\mu^\pm$
   - $B^+ \to K^+\tau^\pm\mu^\mp$
   - $B^0 \to K^{*0}\tau^+\tau^-$

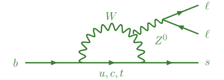
3. Conclusion and prospects

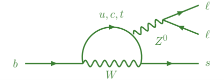
# Introduction

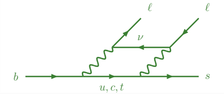
# $b \to s\ell\ell$ transitions

Strongly suppressed in the Standard Model

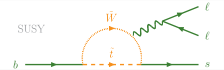
- Only occur through loop-diagrams (Flavour Changing Neutral Current)

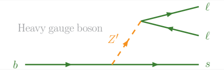


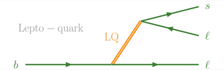




- Sensitivity to new particles increase
  (even more if they generate tree-level contributions)




Allow to search for New Physics at higher scales than TeV

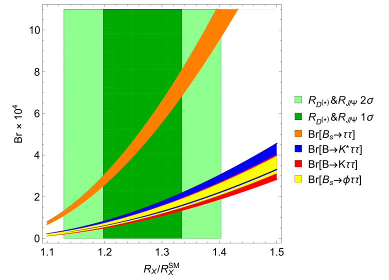
# Why $\tau$'s ?

$\tau$ leptons offer unique window to NP:

- $m_\tau \gg m_\mu \Rightarrow$ different sensitivity to new physics effects
- decay into measurable products $\Rightarrow$ access to variables related to spin couplings
- comparison of transitions with $\tau$ and their counterpart with $\mu \Rightarrow$ LFU tests

Flavour anomalies point to a violation of LFU, which suggests:

- a special role of the third family $\Rightarrow$ enhancement of $b \to s\tau\tau$ decays
  ex: B. Capdevilla *et al.*, PRL 120, 181802 (2018) $\longrightarrow$
- a violation of LFV in many models $\Rightarrow$ enhancement of $b \to s\tau\mu$ decays



# Generalities on $B \to \tau X$ searches

Main features:

- Neutrino(s) escaping detection
- Very large background from $B \to D^{(*)}X$ decays ($D$ life time and mass comparable to $\tau$)

Main analysis ingredients:

- develop and use isolation variables
- use multi-variate techniques

Specific developments:

- custom $B$-mass reconstruction
- custom signal extraction

Each mode has its own specificities. Dedicated strategies must be developed for each search.

# $\tau$ reconstruction

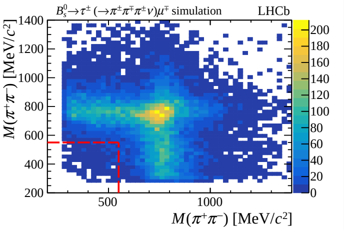
Main $\tau$ decay modes:

| Mode | $\mathcal{B}$ | pros & cons |
|---|---|---|
| $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ | $\sim 18\%$ | trigger on $\mu$<br>no vertexing |
| $\tau^- \to \pi^-\nu_\tau$ | $\sim 11\%$ | B factories only |
| $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ | $\sim 9\%$ | vertexing<br>track multiplicity |
| $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ | $\sim 5\%$ | neutral |

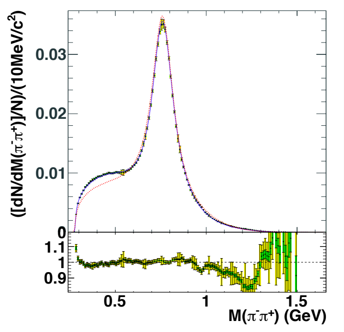
Preferred mode: $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$

- intermediate resonances
  $\tau^- \to a_1(1260)^-\nu_\tau \to \rho^0(770)\pi^-\nu_\tau$
  $\Rightarrow$ helps in the signal selection ↗
- decay model uncertainty ⟶
- unavoidable presence of
  $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ accounted for

arXiv:1905.06614




Phys. Rev. D 88, 093012 (2013)



# Status of some relevant decay modes

| Modes | SM prediction | Exp. (limit @ 90% CL) | LHCb |
|---|---|---|---|
| $B^0 \to \tau^+\tau^-$ | $(2.22 \pm 0.19)\,10^{-8}$ [1] | $< 1.6\,10^{-3}$ [3] | published |
| $B_s^0 \to \tau^+\tau^-$ | $(7.73 \pm 0.49)\,10^{-7}$ [1] | $< 5.2\,10^{-3}$ [3] | |
| $B^+ \to K^+\tau^+\tau^-$ | $(1.20 \pm 0.12)\,10^{-7}$ [2] | $< 2.3\,10^{-3}$ [4] | - |
| $B^0 \to K^{*0}\tau^+\tau^-$ | $(0.98 \pm 0.10)\,10^{-7}$ [2] | - | in progress |
| $B^0 \to \tau^\pm e^\mp$ / $\tau^\pm\mu^\mp$ | × | $< 2.8\,10^{-5}$ [5] / $< 1.2\,10^{-5}$ [6] | published |
| $B_s^0 \to \tau^\pm e^\mp$ / $\tau^\pm\mu^\mp$ | × | - / $< 3.4\,10^{-5}$ [6] | |
| $B^+ \to \pi^+\tau^\pm e^\mp$ / $\pi^+\tau^\pm\mu^\mp$ | × | $< 7.5\,10^{-5}$ [7] / $< 7.2\,10^{-5}$ [7] | - |
| $B^+ \to K^+\tau^\pm e^\mp$ / $K^+\tau^\pm\mu^\mp$ | × | $< 3.0\,10^{-5}$ [7] / $< 4.8\,10^{-5}$ [7] | in progress |
| $B^0 \to K^{*0}\tau^\pm e^\mp$ / $K^{*0}\tau^\pm\mu^\mp$ | × | - | in progress |

LHCb:

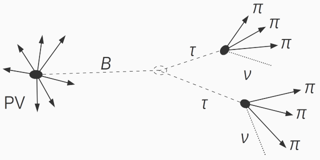
- published analyses use run 1 data ($3\,\text{fb}^{-1}$ @ $\sqrt{s} = 7, 8\ \text{TeV}$)
- analyses in progress use run 1 and (part of) run 2 data ($6\,\text{fb}^{-1}$ @ $\sqrt{s} = 13\ \text{TeV}$)

[1] C. Bobeth *et al.*, PRL 112,101801(2014), [2] B. Capdevila *et al.*, PRL 120,181802(2018) (average over the neutral and charged modes), [3] LHCb, PRL 118,251802(2017), [4] BaBar, PRL 118,031802(2017), [5] BaBar, Phys.Rev.D77,091104(2008), [6] LHCb, arXiv:1905.06614, [7] BaBar, Phys.Rev.D86,012004(2012)

# Illustration with some recent and on-going LHCb analyses

# Illustration with some recent and on-going LHCb analyses

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




Signal extraction:

- fit to the output of a neural network
- templates from signal and control regions

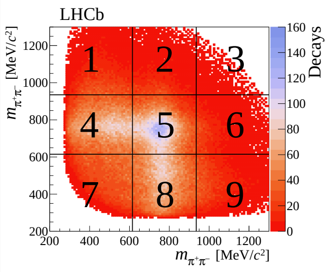
$$\mathcal{N}^{SR}_{data} = s \times \widehat{\mathcal{N}}^{SR}_{sim} + f_b \times \left(\mathcal{N}^{CR}_{data} - s \times \frac{\varepsilon^{CR}}{\varepsilon^{SR}} \times \widehat{\mathcal{N}}^{CR}_{sim}\right)$$

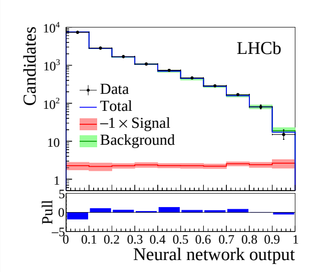
Results:

assuming TAUOLA BABAR-tune model for $\tau$ decay

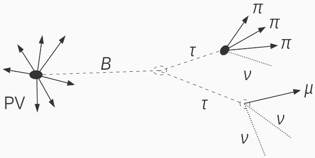
- $\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \cdot 10^{-3}$ @ 95% CL
  $\Rightarrow$ world's first limit
- $\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \cdot 10^{-3}$ @ 95% CL
  $\Rightarrow$ world's best limit (BABAR ÷2)

SR:(5)x(5); CR:(4, 5, 8)x(4, 8); BR:(1, 3, 7, 9)x—



# $B^0_{(s)} \to \tau^+\tau^-$: update with $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$



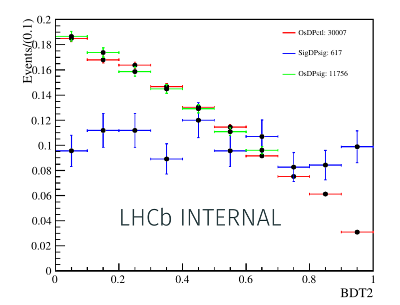

Feasibility study performed with the $(3\pi - \mu)$ final state

- full event selection
- fit strategy
- toys-based estimate of the expected limits

Main outcomes

- large background
- low signal-background separation →
- expected limits are 4-5 × worse than the ones obtained with the $(3\pi - 3\pi)$ final state
- no fit to data attempted

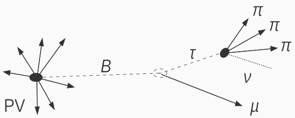
⇒ Summarized in an internal note

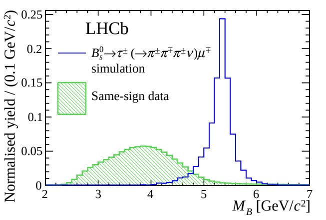


# Illustration with some recent and on-going LHCb analyses

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

arXiv:1905.06614, submitted to PRL



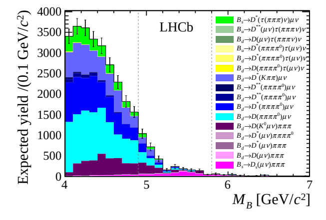




## Custom mass reconstruction

- imposing the $\tau$ mass, decay fully constrained
- $B$ mass reconstructed with $\sigma \simeq 100\,\mathrm{MeV}/c^2$
- allow signal/background separation

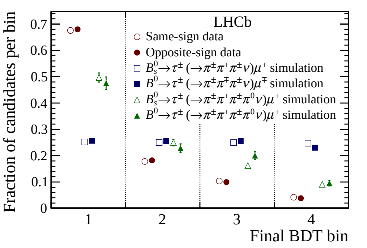
## Event selection

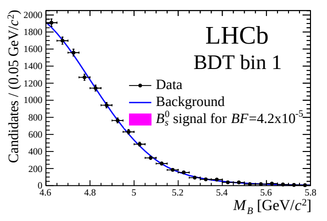
- multivariate classifiers (BDT) trained on same-sign data
- $\tau$ life-time used to remove $B \to D(\to \mu\bar{\nu}_\mu)3\pi X$ decays (peaking)

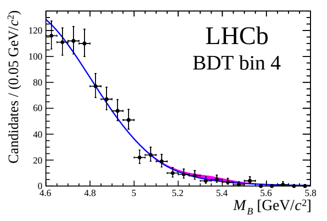


## $B^0_{(s)} \to \tau^\pm \mu^\mp$: Search with run 1 data

arXiv:1905.06614, submitted to PRL




Simultaneous fit to the mass distributions in bins of a final BDT

Results:

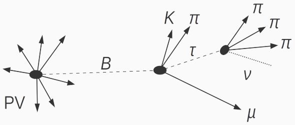
- $\mathcal{B}(B_s^0 \to \tau^\pm \mu^\mp) < 4.2 \cdot 10^{-5}$ @ 95% CL
  $\Rightarrow$ world's first limit
- $\mathcal{B}(B^0 \to \tau^\pm \mu^\mp) < 1.4 \cdot 10^{-5}$ @ 95% CL
  $\Rightarrow$ world's best limit (BaBar ÷2)

# Illustration with some recent and on-going LHCb analyses

$B^0 \to K^{*0}\tau^{\mp}\mu^{\pm}$

## $B^0 \to K^{*0}\tau^{\mp}\mu^{\pm}$: Search with run 1 and part of run 2 data

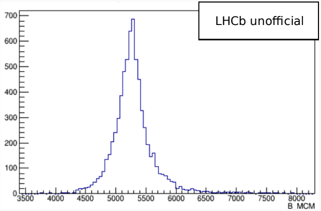
ongoing




Separate limits for

- $B^0 \to K^{*0}\tau^{-}\mu^{+}$, and
- $B^0 \to K^{*0}\tau^{+}\mu^{-}$

Simulated $B^0 \to K^{*0}\tau^{\mp}\mu^{\pm}$ decays



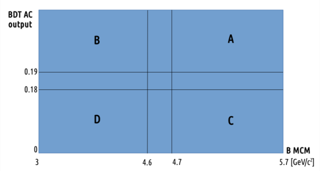

Mass reconstruction : $\sqrt{P_T^2 + M_{ch}^2} + P_T$ →

Background:

- combinatorics + partially rec. $B$ decays
- suppressed using multivariate techniques

Signal yield extraction

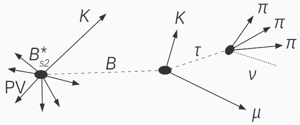
- counting experiment
- background yield extracted from 2D control regions: A = BC/D →



# Illustration with some recent and on-going LHCb analyses

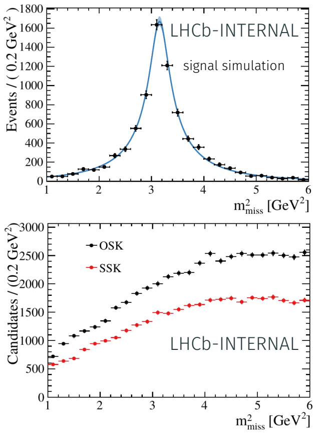
$B^+ \to K^+\tau^\pm\mu^\mp$

# $B^+ \to K^+\tau^\pm\mu^\mp$: Search with run 1 and run 2 data




Use $B^*_{s2} \to K^- B^+ decays$

- $\sim$1% of $B^+$
- inclusive $\tau$




Missing mass reconstruction:

- $E_{B^+}$ reconstructed from $B^*_{s2}$ and $B^+$ vertices
- $E_{miss} = E_{B^+} - E_{K\pi}$

Strategy:

- fit $m^2_{miss}$ in bins of a BDT

Sensitivity:

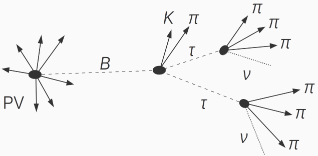
- expect few $10^{-5}$

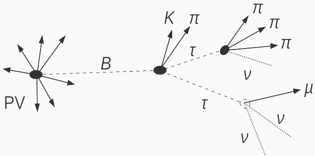
# Illustration with some recent and on-going LHCb analyses

$B^0 \to K^{*0}\tau^+\tau^-$

# $B^0 \to K^{*0}\tau^+\tau^-$: Search with run 1 and run 2 data



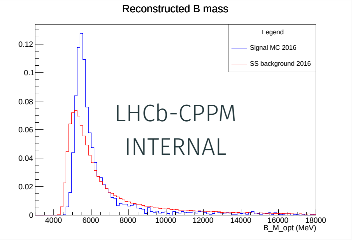



Exploring both $(3\pi - 3\pi)$ and $(3\pi - \mu)$
Very challenging analysis

- mass reconstructed using the $\tau$-mass and decay vertices constraints does not provide enough signal–background separation
- large candidate multiplicity
- huge background

→



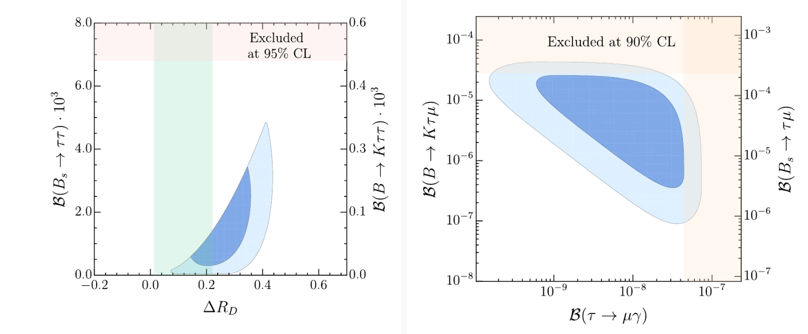

More details in Jacopo's talk tomorrow

# Conclusion and prospects

# Conclusion

Current bounds set on rare $B$ decays with $\tau$ already provide strong constraints on some models proposed to explain the flavour anomalies, e.g.

C. Cornella, J. Fuentes-Martin and G. Isidori, JHEP 07(2019)168 v1

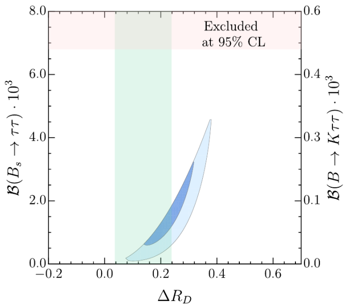


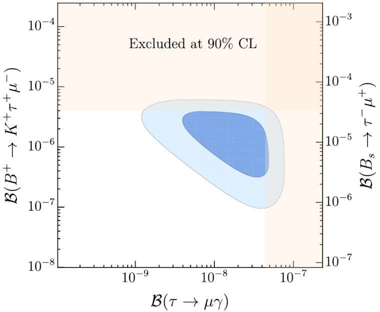

Before $B_s^0 \to \tau^\pm \mu^\mp$ measurement

# Conclusion

Current bounds set on rare $B$ decays with $\tau$ already provide strong constraints on some models proposed to explain the flavour anomalies, e.g.

C. Cornella, J. Fuentes-Martin and G. Isidori, JHEP 07(2019)168 v2

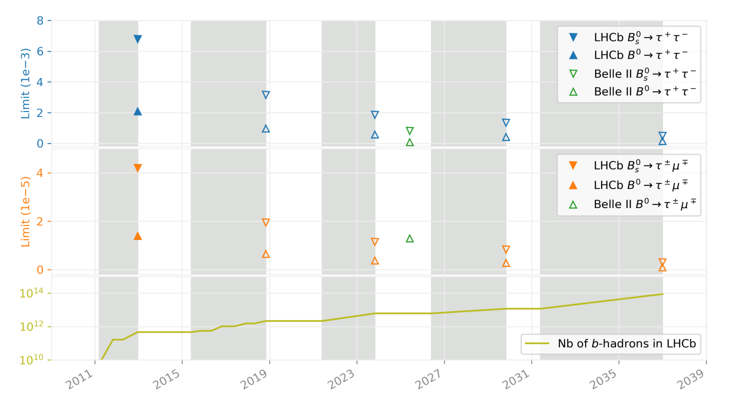



After $B_s^0 \to \tau^\pm \mu^\mp$ measurement

# Prospects

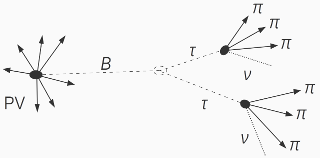
Scaling the current limits with the expected increase in statistics




Belle II with $5\,\mathrm{ab}^{-1}$ @ $\Upsilon(5S)$ for the $B_s^0$ mode and $50\ \mathrm{ab}^{-1}$ @ $\Upsilon(4S)$ for the $B^0$ modes

[Belle II Physics book, arXiv:1808.10567]

# $B^0_{(s)} \to \tau^+\tau^-$: update with run2 data with $(3\pi - 3\pi)$




Analysis update with 2016-2017 data ($\sim 3.5\,\mathrm{fb}^{-1}$)

- $\times$ 2 the run 1 statistics
- reproduce & improve
  $\Rightarrow$ better SR and CR regions agreement in the final NN
- toys-based estimate of the expected limits
  $\Rightarrow$ sensitivity as expected

Remaining

- optimize selection and final NN
- add 2018 (and 2015) data ($\sim 2.5\,\mathrm{fb}^{-1}$)
- evaluate systematic uncertainties
- final fit combined with run 1