Rare B decays with final state including τ leptons

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Introduction

Why rare B decays with τ?

- Rare decays are good probes to search for physics beyond the SM
- Recent hints of LFU stressed the importance of the 3rd family

	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$	$\tau\mu$	μe
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)}\tau\tau$ $\to$ 100×SM	$B \to K^{(*)}\nu\nu$ O(1)	$B \to K\tau\mu$ $\to \sim 10^{-6}$	$B \to K\mu e$???
$b \to d$	$B_d \to \mu\mu$ $B \to \pi\mu\mu$ $B_s \to K^{(*)}\mu\mu$ O(20%) $[R_K = R_\pi]$	$B \to \pi\tau\tau$ $\to$ 100×SM	$B \to \pi\nu\nu$ O(1)	$B \to \pi\tau\mu$ $\to \sim 10^{-7}$	$B \to \pi\mu e$???

G. Isidori, LHCb Implication WS (2017)

Status of some relevant decay modes

Modes	SM prediction	Exp.
$B^0 \to \tau^+\tau^-$	$(2.22 \pm 0.19)\,10^{-8}$ [1]	$< 1.6\,10^{-3}$ [3]
$B_s^0 \to \tau^+\tau^-$	$(7.73 \pm 0.49)\,10^{-7}$ [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]	-
$B^0 \to \tau^\pm e^\mp /\ \tau^\pm\mu^\mp$	-	$< 2.8\,10^{-5}$ / $< 2.2\,10^{-5}$ [5]
$B_s^0 \to \tau^\pm e^\mp /\ \tau^\pm\mu^\mp$	-	-
$B^+ \to \pi^+\tau^\pm e^\mp /\ \pi^+\tau^\pm\mu^\mp$	-	$< 7.5\,10^{-5}$ / $< 7.2\,10^{-5}$ [6]
$B^+ \to K^+\tau^\pm e^\mp /\ K^+\tau^\pm\mu^\mp$	-	$< 3.0\,10^{-5}$ / $< 4.8\,10^{-5}$ [6]
$B^0 \to K^{*0}\tau^\pm e^\mp /\ K^{*0}\tau^\pm\mu^\mp$	-	-

[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] BaBar, Phys.Rev.D86,012004(2012)

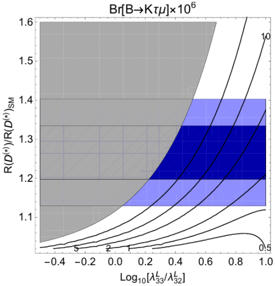
This talk:

Current searches for $B^0_{(s)} \to \tau^+\tau^-$, $B^0_{(s)} \to \tau^\pm\mu^\mp$ and $B^0 \to K^{*0}\tau^\pm\mu^\mp$ at LHCb

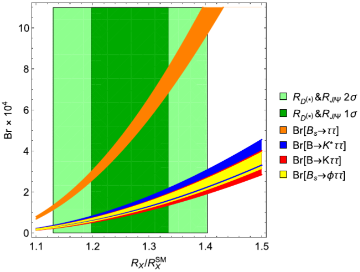
Some BSM predictions

Models proposed to explain the flavour anomalies
Very large enhancements may occur !

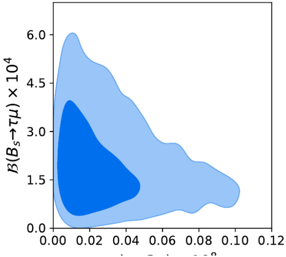
A. Crivellin *et al.*, JHEP09(2017)040



B. Capdevila *et al.*, PRL 120, 181802 (2018)



M. Bordone *et al.*, arXiv:1805.09328



Rare B decays with final state including τ

- Challenging search:
  always at least a missing neutrino in the final state
- Tau decay modes
  - one-prong decays
    $\tau^- \to e^- \overline{\nu}_e \nu_\tau$:$\mathcal{B} =\sim 17\%$
    $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$: $\mathcal{B} =\sim 17\%$
    $\tau^- \to \pi^- \nu_\tau$: $\mathcal{B} =\sim 11\%$
    $\tau^- \to \rho^- \nu_\tau$: $\mathcal{B} =\sim 22\%$
  - three-prong decays
    $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ $\mathcal{B} =\sim 9\%$
    $\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ $\mathcal{B} =\sim 5\%$
- BaBar & Belle (II) can constraint the kinematic of the decay using the information of the other B and the centre of mass energy of the beam
  Can use the one-prong decays, accessing $\sim 70\%$ of the τ decays
- Not possible in hadron collider, even less with a forward detector
  In LHCb: focus on the three-prong decays, allowing to reconstruct the τ decay vertex

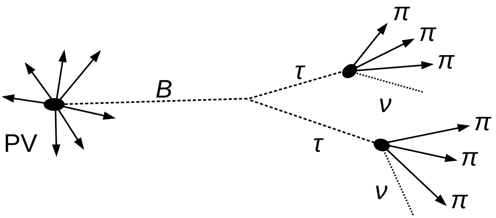
$B^0_{(s)} \to \tau^+\tau^-$

LHCb Run 1 - published

PRL 118, 251802 (2017)

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

PRL 118, 251802 (2017)

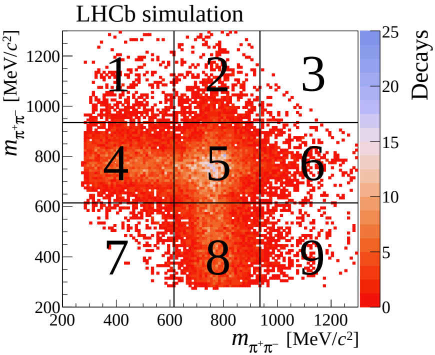


- Imposing B, τ, ν mass constraints, the τ's momenta can be computed analytically
  $\to$ original method developed by J. Charles & A. Morda (A. Morda thesis)
  - approximations in the resolution + detector resolution
    $\to$ many events w/o real solutions
  - intermediate quantities associated with the method
    $\to$ used to discriminate signal from background

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

PRL 118, 251802 (2017)

Exploit: $\tau^- \to a_1^-(1260)\nu_\tau \to \rho(770)\pi^-\nu_\tau \to \pi^-\pi^+\pi^-\nu_\tau$



- Signal region:
  both τ in 5
- Control region:
  one τ in (4,5,8) and the other in (4,8)
- Background region:
  at least one tau in (1,3,7,9)

Selection:

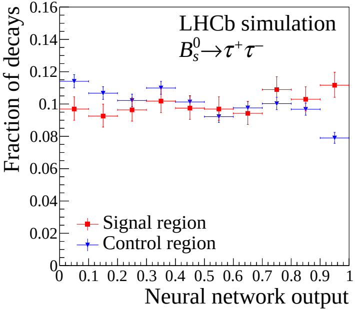
- Isolation variables (track & composite, neutral, vertex)
- Multivariate classifier (NN) trained using the background region

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

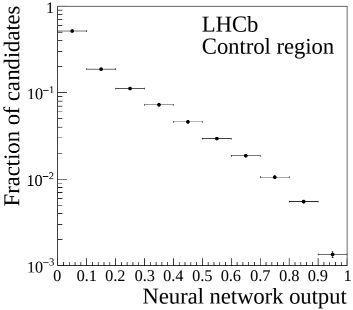
PRL 118, 251802 (2017)

- 1-dimensional histogram fit to the output of a neural network (flat output for signal between 0 and 1)
- signal templates from simulation ($\widehat{\mathcal{N}}^{\text{SR}}_{\text{sim}}$ and $\widehat{\mathcal{N}}^{\text{CR}}_{\text{sim}}$)
- background template from data control region ($\widehat{\mathcal{N}}^{\text{CR}}_{\text{data}}$)

$\widehat{\mathcal{N}}^{\text{SR}}_{\text{sim}}$ and $\widehat{\mathcal{N}}^{\text{CR}}_{\text{sim}}$



$\widehat{\mathcal{N}}^{\text{CR}}_{\text{data}}$



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

PRL 118, 251802 (2017)

Events fraction in the 3 categories:

	simulated signal	selected candidates (data)
Signal	16%	7%
Control	58%	47%
Background	13%	37%

Fit model:

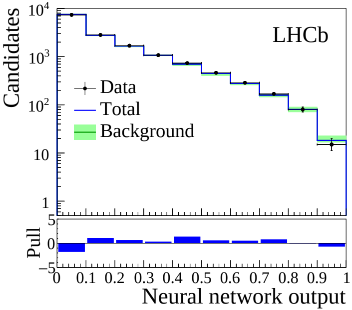
$$\mathcal{N}^{\text{SR}}_{\text{data}} = s \times \widehat{\mathcal{N}}^{\text{SR}}_{\text{sim}} + f_b \times \left(\mathcal{N}^{\text{CR}}_{\text{data}} - s \times \frac{\varepsilon^{\text{CR}}}{\varepsilon^{\text{SR}}} \times \widehat{\mathcal{N}}^{\text{CR}}_{\text{sim}} \right)$$

- s: signal yield (free)
- f_b: background normalisation (free)
- ε^{CR},ε^{SR} : signal efficiencies in the control and signal regions (from simulation)

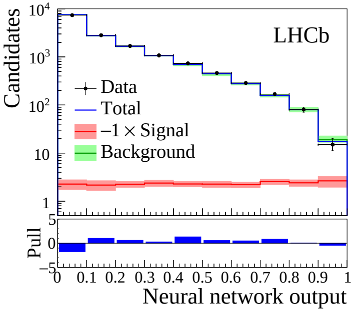
$B_s^0 \to \tau^+\tau^-$ fit to data

PRL 118, 251802 (2017)

With background only model:



Nominal fit:



$$s = -23 \pm 71$$

- compatible with the background only hypothesis

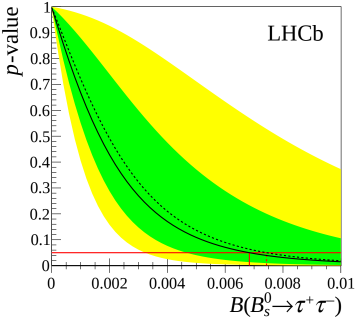
$\to$ set an upper limit on $\mathcal{B}$ using $B^0 \to D^+ D_s^-$ as a normalisation mode

$B^0_{(s)} \to \tau^+\tau^-$ limits on branching fractions

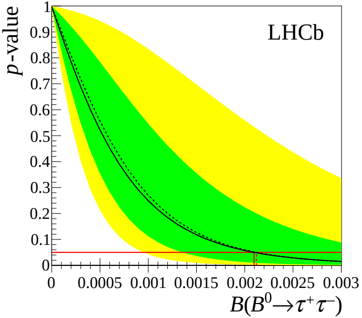
PRL 118, 251802 (2017)

Two independent fits, one for B^0_s and an other for B^0

$B^0_s \to \tau^+\tau^-$:



$B^0 \to \tau^+\tau^-$:



$$\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \cdot 10^{-3} \,@\, 95\% \text{ CL}$$
$$\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \cdot 10^{-3} \,@\, 95\% \text{ CL}$$

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

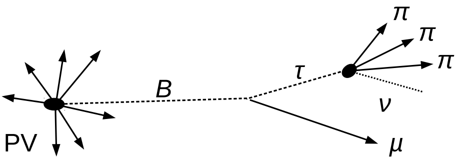
- LHCb:
  - Presented results are using only Run 1 data
    $\mathcal{B}(B^0_s \to \tau^+\tau^-) < 6.8 \cdot 10^{-3}$ @ 95% CL
    $\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \cdot 10^{-3}$ @ 95% CL
  - Adding the $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ mode:
    $\to$ no significant improvement to the expected limit
  - Future reaches (Physics case for an LHCb Upgrade II)
    $\mathcal{B}(B^0_s \to \tau^+\tau^-) \lesssim 1.3 \cdot 10^{-3}$ after LHCb Upgrade I
    $\mathcal{B}(B^0_s \to \tau^+\tau^-) \lesssim 5 \cdot 10^{-4}$ after LHCb Upgrade II
- Belle II 5 ab^{-1} (Belle II Physics book):
  - $\mathcal{B}(B^0_s \to \tau^+\tau^-) \lesssim 8 \cdot 10^{-4}$ with 5 ab^{-1} @ $\Upsilon(5S)$
  - $\mathcal{B}(B^0 \to \tau^+\tau^-) \lesssim 1 \cdot 10^{-4}$ with 50 ab^{-1} @ $\Upsilon(4S)$

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

LHCb Run 1 - on going analysis

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

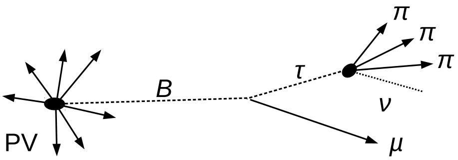
on going analysis



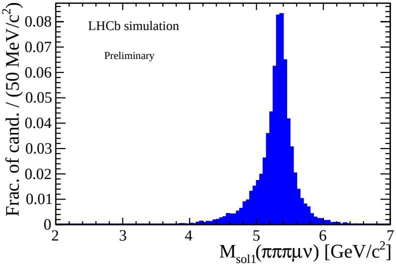
- Easier than $B^0_{(s)} \to \tau^+\tau^-$
  - only one missing neutrino
  - only 4 tracks
  - the muon points to the B vertex
- Enough constraints to compute the B mass

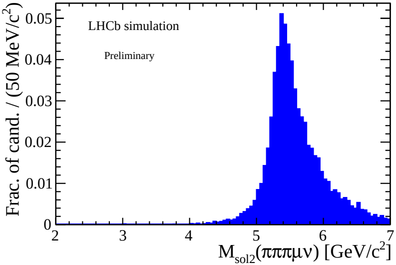
$B^0_{(s)} \to \tau^\pm \mu^\mp$

on going analysis



- B mass computed up to a 2-fold ambiguity (imposing the τ mass)
- ~ 70 % of physical solution - less for background
- 1st solution gives largest separation between signal and background





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

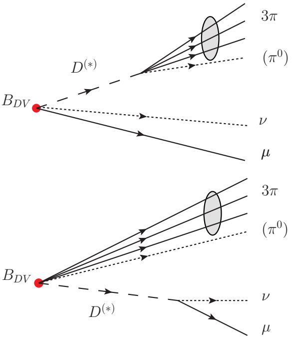
on going analysis

Main backgrounds:

- combinatorics
- partially reconstructed B decays

Backgrounds samples:

- same-sign candidates ($\tau^\pm \mu^\pm$)
  $\to$ selection optimisation
- simulation
  $\to$ qualitative studies
  - exclusive decays - non-exhaustive list
  - inclusive b-samples - statistically limited



Backgrounds rejection:

- multivariate classifiers
  including isolation variables
- dedicated cuts against peaking background (e.g. $B^0_{(s)} \to D^-_{(s)}(\to \mu^- \overline{\nu}_\mu)\pi^+\pi^-\pi^+$)

Signal yield extraction:

- Simultaneous fit to the mass distributions in categories with different signal over background ratios

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

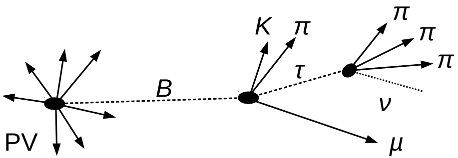
- LHCb:
  - On going analysis using only Run 1 data
  - Subject of a thesis defended in September
  - Expect (Physics case for an LHCb Upgrade II)
    $\mathcal{B}(B^0_s \to \tau^\pm \mu^\mp) \lesssim$ few 10^{-5} after Run 1&2
    $\mathcal{B}(B^0_s \to \tau^\pm \mu^\mp) \lesssim$ few 10^{-6} after LHCb Upgrade II
- Belle II 5 ab^{-1} (Belle II Physics book):
  - $\mathcal{B}(B^0 \to \tau^\pm \mu^\mp) \lesssim 1 \cdot 10^{-5}$ with 50 ab^{-1}

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

LHCb Run 1&2 - on going analysis

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

on going analysis



- Comparison with $B^0_{(s)} \to \tau^{\pm}\mu^{\mp}$
  - 6 tracks ! but:
  - only one missing neutrino
  - the B decay vertex is reconstructed

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

on going analysis

Mass reconstruction:

- use the corrected mass: $\sqrt{P_{\mathrm{T}}^2 + M_{ch}^2} + P_{\mathrm{T}} \to$

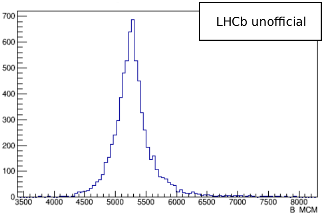
Background:
combinatorics + partially rec. B decays

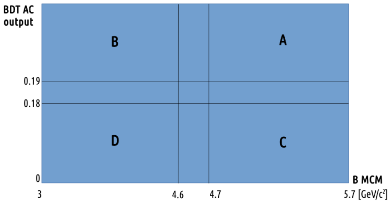
- suppressed using multivariate techniques

Signal yield extraction

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

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





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

- LHCb:
  - On going analysis using Run 1 data - updated soon with Run 2 ?
  - Subject of a thesis defended in September
  - Expect (Physics case for an LHCb Upgrade II) $\mathcal{B}(B^0 \to K^{*0}\tau^\pm\mu^\mp) \lesssim$ few 10^{-6} (Run 1&2)
- Belle II 5 ab^{-1} (Belle II Physics book):
  - $\mathcal{B}(B^0 \to \tau^\pm\mu^\mp) \lesssim 1 \cdot 10^{-5}$ with 50 ab^{-1}

Conclusions

- Many models proposed to explain the flavour anomalies predicts large enhancements for rate of rare B decays with τ in the final state
- The searches for $B^0_{(s)} \to \tau^\pm \mu^\mp$ and $B^0 \to K^{*0} \tau^\pm \mu^\mp$ are well advanced
- Others are progressing ($B^+ \to K^+ \tau^\pm \mu^\mp$) or will start soon ($B^0 \to K^{*0} \tau^+ \tau^-$)
- Hope for more news in the near future ...