$B \to \mu^+\mu^-$ and other very rare B decays at LHCb

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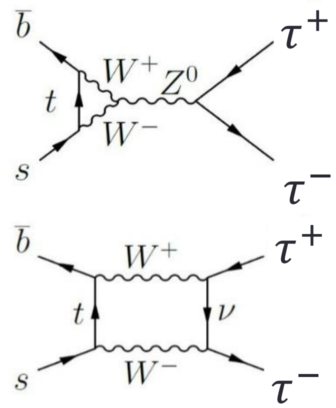
on behalf of the LHCb collaboration

BEAUTY 2019

Ljubljana, 30 September – 4 October 2019

Introduction

- FCNC are forbidden in SM at tree level. Possible through loop diagrams:
  - Suppressed
  - Potential sizeable interference with transitions mediated by new particles



- $B \to l^+l^-$ decays belong to this category
  - Further helicity suppressed
  - Theoretically clean SM predictions
  - ➔ Powerful probes of physics beyond SM
- Lepton flavour violating transitions are experimentally forbidden in SM
  - If mediated through neutrino mixing, predicted rates are $< 10^{-50}$
  - Significantly enhanced in many SM extensions, up to already testable rates
- In this talk:
  - Status and prospects of measurements of $B \to l^+l^-$ and B LFV decays at LHCb.
- For discussions of other rare B decays at LHCb see:
  - P. Krokovny, *Radiative decays at LHCb*, Tue 1 October
  - F. J. Kress, *$b \to sll$ and friends (studies with muons) at LHCb*, Wed 2 October
  - C. Langenbruch, *$b \to sll$ and friends ($R_{K^{(*)}}$, …) at LHCb*, Wed 2 October
  - M. J. Tilley, *Semileptonic B decays at LHCb*, Thu 3 October

Selection of $B^0_{(s)} \to \mu^+\mu^-$ decays

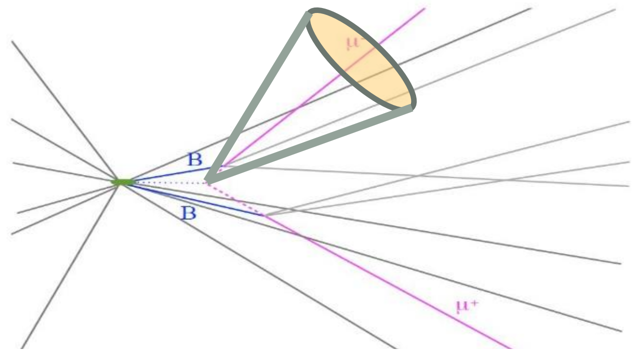
PRL 118, 191801 (2017)

- FCNC processes strongly helicity-suppressed. Theoretically very clean.

$$BF(B^0_s \to \mu^+\mu^-) = (3.57 \pm 0.17) \times 10^{-9}$$
$$BF(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

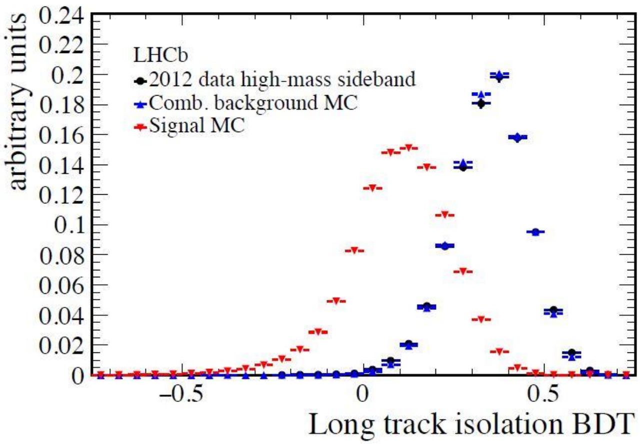
PRL 112 (2014) 101801
EPJC 77 (2017) 112

- Dataset: Run 1 + 1.4 fb^{-1} of Run 2 (tot: 4.4 fb^{-1})
- Basic selection requirement:
  - two oppositely-charged muon tracks with common vertex displaced from primary vertex
  - $m_{\mu\mu}$ mass peaking at the $B^0_{(s)}$ mass



Typical combinatorial background event with two muons from different *b* decays

- In practice, complex analysis due to low signal/large background rates
- Most abundant background is combinatorial
  - muons from different b quark decays
  - strongly suppressed with multivariate operator (BDT) using track isolation, topo/geom information

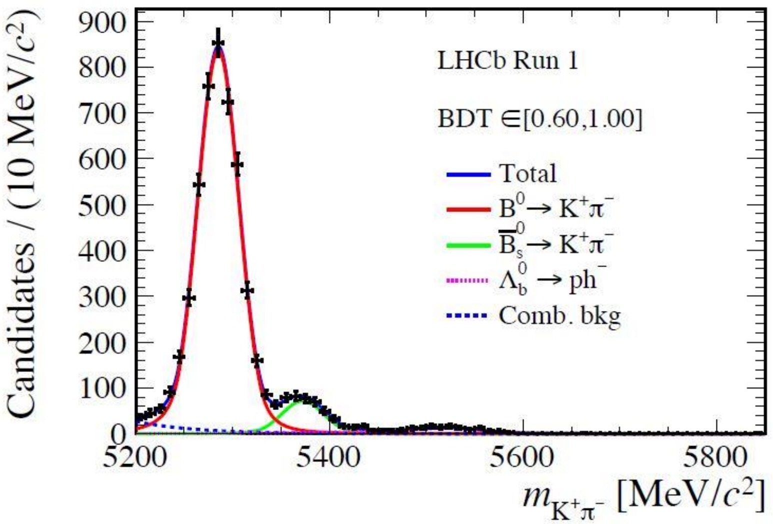


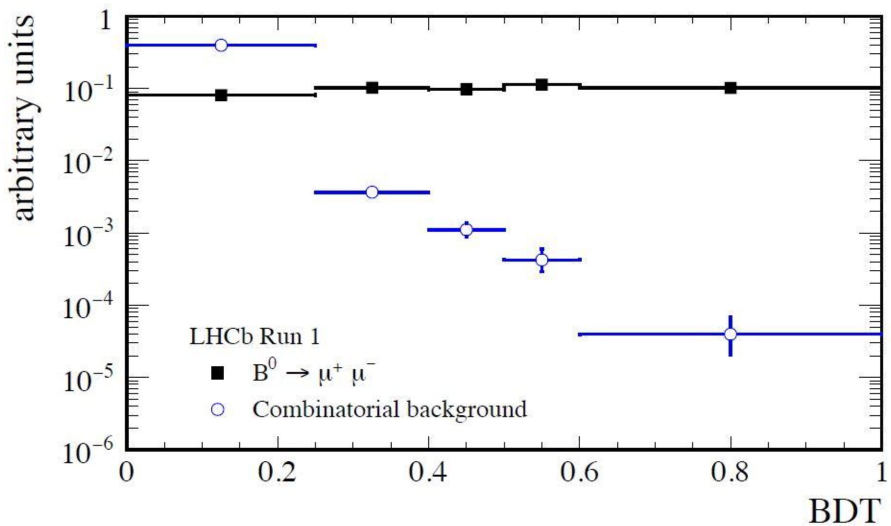
BDT calibration

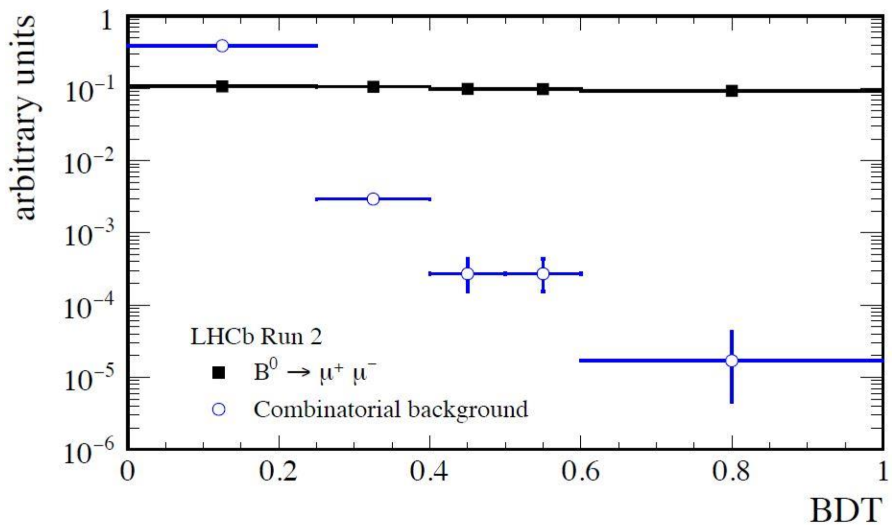
PRL 118, 191801 (2017)

- BDT output flat for B^0 signal and peaking at zero for combinatorial background
- $B^0 \to \mu\mu$ BDT shape from $B^0 \to K^+\pi^-$ in data and corrected for trigger and PID selection. Additional lifetime-related correction for $B_s^0 \to \mu\mu$

$B^0 \to K^+\pi^-$ selection in data, BDT>0.6





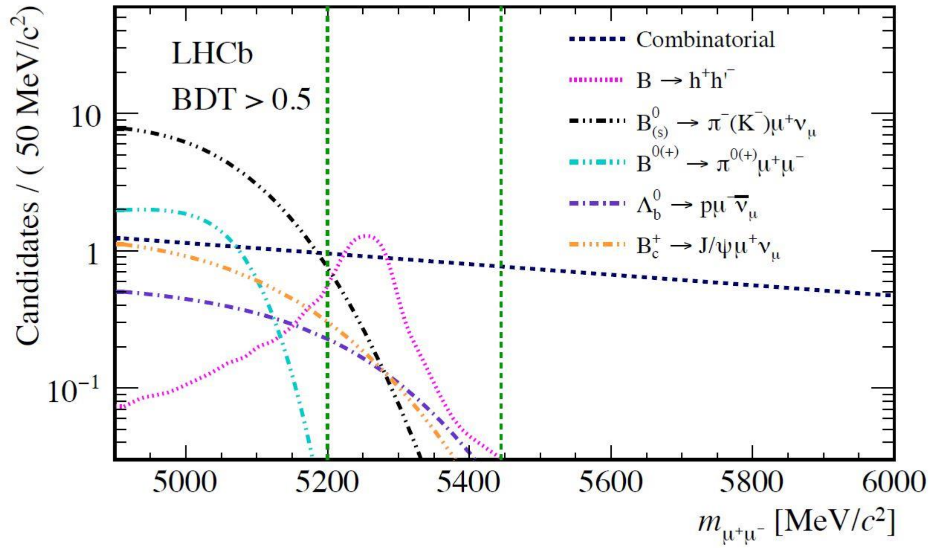


Physics backgrounds

PRL 118, 191801 (2017)

Yields of main *physics* backgrounds *in signal region* with BDT>0.5:

$B \to h^+h'^-$	2.9 ± 0.3
$B_c^+ \to J/\psi\mu^+\nu_\mu$	1.2 ± 0.2
$B^0_{(s)} \to h^-\mu^+\nu_\mu$	0.80 ± 0.06
$\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$	0.7 ± 0.2
$B^{0(+)} \to \pi^{0(+)}\mu^+\mu^-$	negligible



- These decays are taken into account in the fit to $m_{\mu\mu}$. Mass shapes and yield *vs* BDT determined from simulated samples with misID probability calibrated on data
- $B \to h^+h'^-$ particularly dangerous because peaks in the B^0 signal region
  - Alternative estimates of $B \to h^+h'^-$ and $B^0_{(s)} \to h^-\mu^+\nu_\mu$ yields from $h\mu$ mass spectra in data
- SM ISR $B_s^0 \to \mu^+\mu^-\gamma$ has negligible impact on signal yield from fit
- -60% combinatorial background reduction wrt previous analysis by optimizing BDT+PID

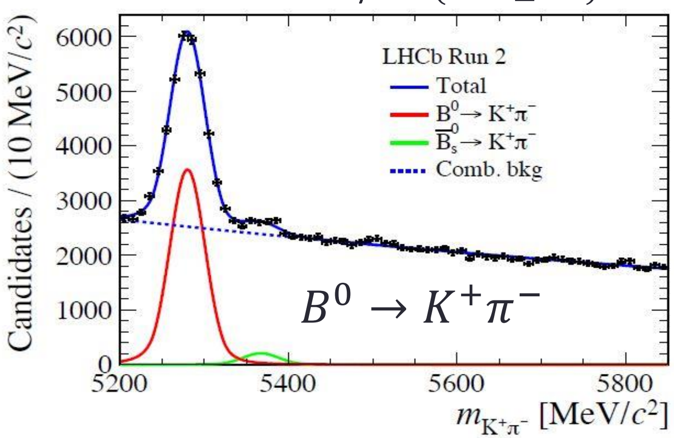
Normalisation

PRL 118, 191801 (2017)

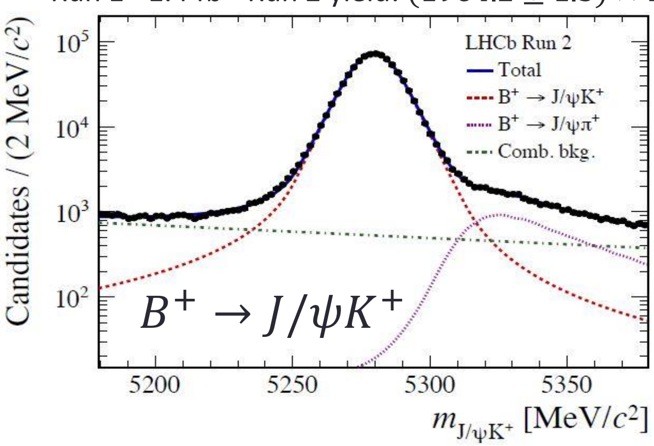
$$BF(B^0_{(s)} \to \mu\mu) = \underbrace{\frac{\overbrace{BF_{norm}}^{B\text{-factories}}}{N_{norm}}}_{\text{norm. channels}} \times \underbrace{\frac{\epsilon^{Acc}_{norm}}{\epsilon^{Acc}_{sig}} \times \frac{\epsilon^{RecSel|Acc}_{norm}}{\epsilon^{RecSel|Acc}_{sig}} \times \frac{\epsilon^{Trig|RecSel}_{norm}}{\epsilon^{Trig|RecSel}_{sig}}}_{\text{MC + input from data}} \underbrace{\frac{f_d}{f_{d(s)}}}_{\text{LHCb}} \underbrace{N_{B^0_{(s)}\to\mu\mu}}_{\text{fit of } m_{\mu\mu}} = \alpha_{(s)} \times N_{B^0_{(s)}\to\mu\mu}$$

- $\alpha_s = (5.7 \pm 0.4) \times 10^{-11}$; $\alpha = (1.60 \pm 0.04) \times 10^{-11}$ — Weighted averages from $B^+ \to J/\psi K^+$ and $B^0 \to K^+\pi^-$
- $f_s/f_d = 0.259 \pm 0.015$ measured by LHCb at 7 TeV
- Procedure checked by measuring $BF(B^0 \to K\pi)/BF(B^+ \to J/\psi\, K^+)$ and $BF(B_s \to J/\psi\, \phi)/BF(B^+ \to J/\psi\, K^+)$

Run 1+ 1.4 fb^{-1} Run 2 yield: $(31.3 \pm 0.4) \times 10^3$



Run 1+ 1.4 fb^{-1} Run 2 yield: $(1964.2 \pm 1.5) \times 10^3$



Results

PRL 118, 191801 (2017)

- BFs measured from UML fit of $m_{\mu\mu}$ simultaneously in 5 bins of BDT:

$BF(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$ **$7.8\,\sigma$**

First observation from single experiment

$BF(B^0 \to \mu^+\mu^-) = (1.5^{+1.2}_{-1.0}{}^{+0.2}_{-0.1}) \times 10^{-10}$ $1.6\,\sigma$

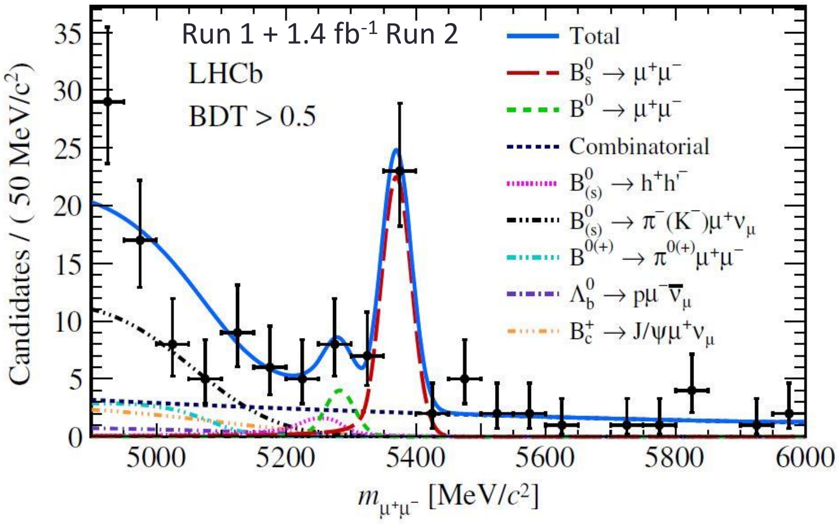
$< 3.4 \times 10^{-10}$ at 95% CL

- Results consistent with SM

NB: $BF(B_s^0 \to \mu\mu)$ assumes $\tau_{B_s^0\to\mu\mu} = \tau_{B_s}/(1-y_s)$ (i.e. $A_{\Delta\Gamma} = 1$)

It increases by 4.6% (10.9%) if $A_{\Delta\Gamma} = 0\ (-1)$ (the sel efficiency decreases)

- Main sources of systematic uncertainty:
  - $BF(B_s^0 \to \mu^+\mu^-)$: knowledge of f_s/f_d
  - $BF(B^0 \to \mu^+\mu^-)$: $B \to hh$ backgrounds



$B_s^0 \to \mu^+\mu^-$ effective lifetime

PRL 118, 191801 (2017)

- The effective lifetime is an additional probe for NP complementary to the BF

$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\,\Gamma(B_s(t)\to\mu^+\mu^-)dt}{\int_0^\infty \Gamma(B_s(t)\to\mu^+\mu^-)dt}$$

- In terms of the physics parameters:

$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1-y_s^2}\left(\frac{1+2A_{\Delta\Gamma}^{\mu^+\mu^-}y_s+y_s^2}{1+A_{\Delta\Gamma}^{\mu^+\mu^-}y_s}\right)$$

$\tau_{B_s^0} = 1.510 \pm 0.004\,ps$

$y_s \equiv \tau_{B_s}\Delta\Gamma/2 = 0.062 \pm 0.006$

$A_{\Delta\Gamma}^{\mu^+\mu^-}$ = 1 in SM, can be in $[-1,1)$ if NP occurs

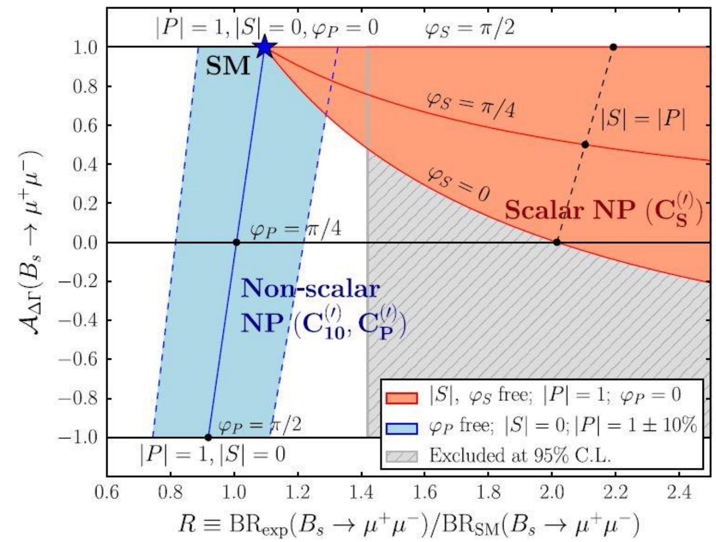
- Measured from fit to the $B_s^0 \to \mu^+\mu^-$ decay time ($\int L dt = 4.4\, fb^{-1}$)

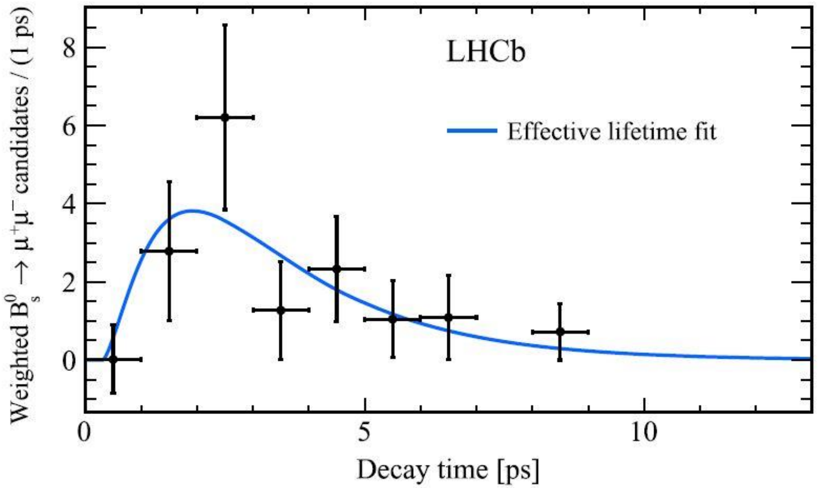
$$\tau(B_s^0 \to \mu^+\mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

First measurement of this quantity

At present, consistent with any value of $A_{\Delta\Gamma}^{\mu^+\mu^-}$

from PRL 109, 041801 (2012)





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

PRL 118 (2017) 251802

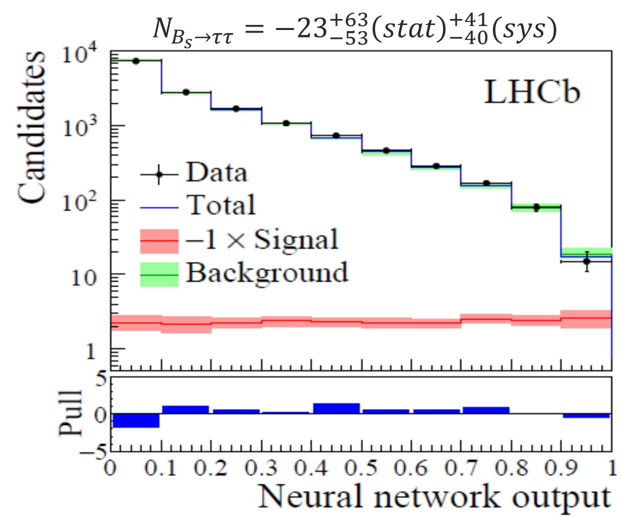
- In SM FCNC processes analogous to $B^0_{(s)} \to \mu^+\mu^-$ but less helicity-suppressed

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

PRL 112 (2014) 101801

$$\frac{\mathcal{B}(B^0_{(s)} \to \tau^+\tau^-)}{\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-)} = \frac{m_\tau^2}{m_\mu^2} \times \sqrt{\frac{m_B^2 - 4m_\tau^2}{m_B^2 - 4m_\mu^2}} \sim \mathbf{210}$$

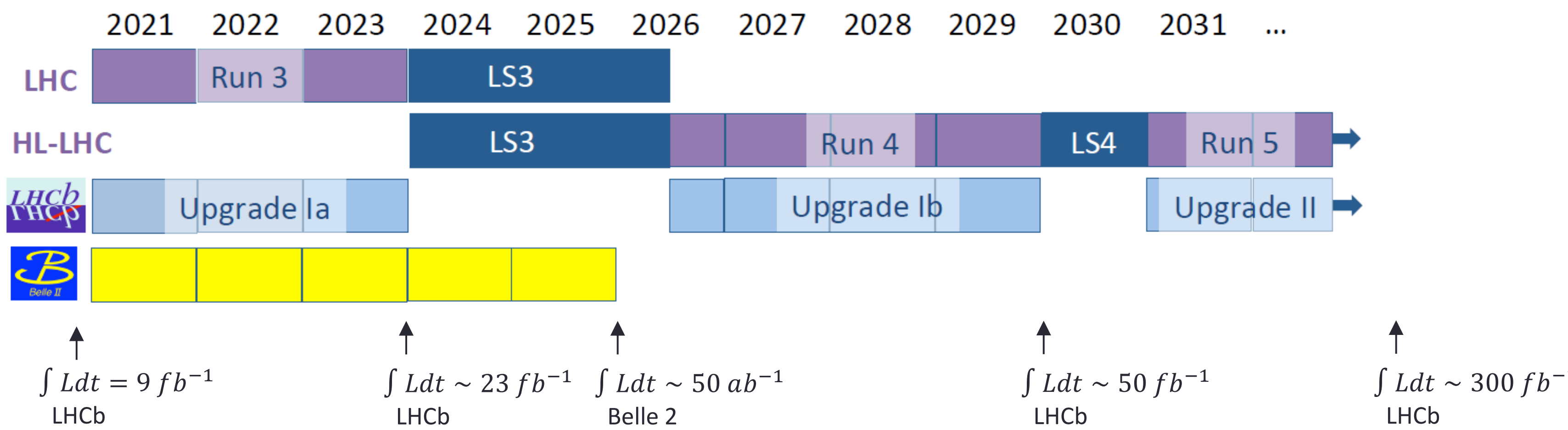
- NP models explaining observed SM tensions in $b \to sl^+l^-$ and $b \to cl^-\bar{\nu}_l$ transitions allow possible increase of BF by orders of magnitude
- $\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$. τ decay model tuned on BaBar data
- Approximate reconstruction of $B \to \tau^+\tau^-$ using geo and mass constraints
- NN built with geometric, kinematic and isolation variables to separate signal and background
- Run 1 dataset (3 fb^{-1})
- Signal extracted from fit to NN in signal region
  - Yield→BF using $B^0 \to D^+[K^-\pi^+\pi^+]D_s^-[K^+K^-\pi^-]$



$$BF(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ @ } 95\%\ CL$$ first limit

$$BF(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ @ } 95\%\ CL$$ x 2.6 improvement wrt BaBar limit

Prospects for $B \to l^+ l^-$ at LHCb



	now	$\int Ldt = 23$ fb^{-1}	$\int Ldt = 300$ fb^{-1}
err $BF(B_s^0 \to \mu^\pm \mu^\mp)$	0.65×10^{-9}	0.30×10^{-9} [1]	0.13×10^{-9} [1]
rel err $BF_{B^0 \to \mu\mu} / BF_{B_s^0 \to \mu\mu}$	90%	34% [1]	10% [1]
rel err $\tau_{B_s^0 \to \mu\mu}$	21%	8% [1]	2% [1]
err $S_{B_s^0 \to \mu\mu}$	–	–	0.2 [1]
UL $BF(B_s^0 \to \tau^+ \tau^-)$	6.8×10^{-3}	1.9×10^{-3} [2]	5×10^{-4} [1]

LHCb $B^0_{(s)} \to e^+ e^-$ measurement in progress

[1] CERN-LHCb-PUB-2018-009

[2] From current limit assuming $1/\sqrt{\int Ldt}$ scaling

Lepton flavour violating B decays

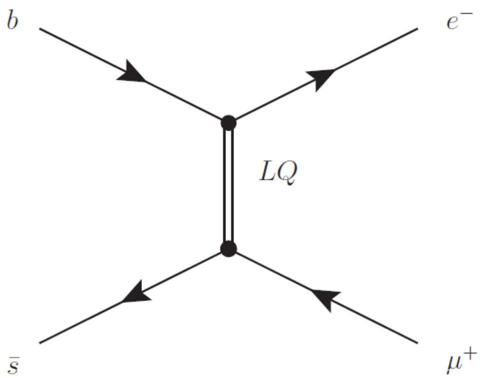
- The only lepton flavour violating (LFV) phenomenon observed so far is neutrino oscillation. If this was the only LFV mechanism, LFV B decay rates would be $< 10^{-50}$: far beyond current and future experimental reach.
- Many models proposed to explain the tensions with SM in $b \to s l^+ l^-$ and $b \to c l^- \overline{\nu}_l$ transitions ($R_{K^{(*)}}$, $R_{D^{(*)}}$, etc) naturally allow sizeable LFV B rates, e.g. models with Z', with scalar or vector LQ, or PS[3].

for instance:

Becirevic, Kosnik, Sumensari, Zukanovich Funchal, JHEP 11 (2016) 035
Crivellin, Hofer, Matias, Nierste, Pokorski, Rosiek, PRD92 (2015) 054013
Hiller, Loose, Schonwald, JHEP 12 (2016) 027
Bordone, Cornella, Fuentes-Martin, Isidori JHEP 1810 (2018) 148

➔ it is interesting to search for LFV B decays

$\overline{B_s^0} \to \mu^+ e^-$



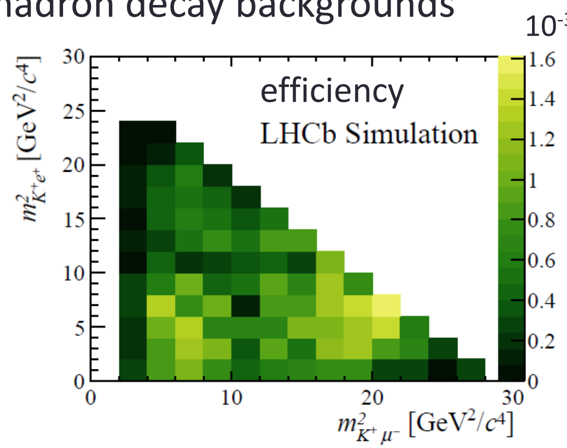
Search for $B^+ \to K^+\mu^\pm e^\mp$

arXiv:1909.01010

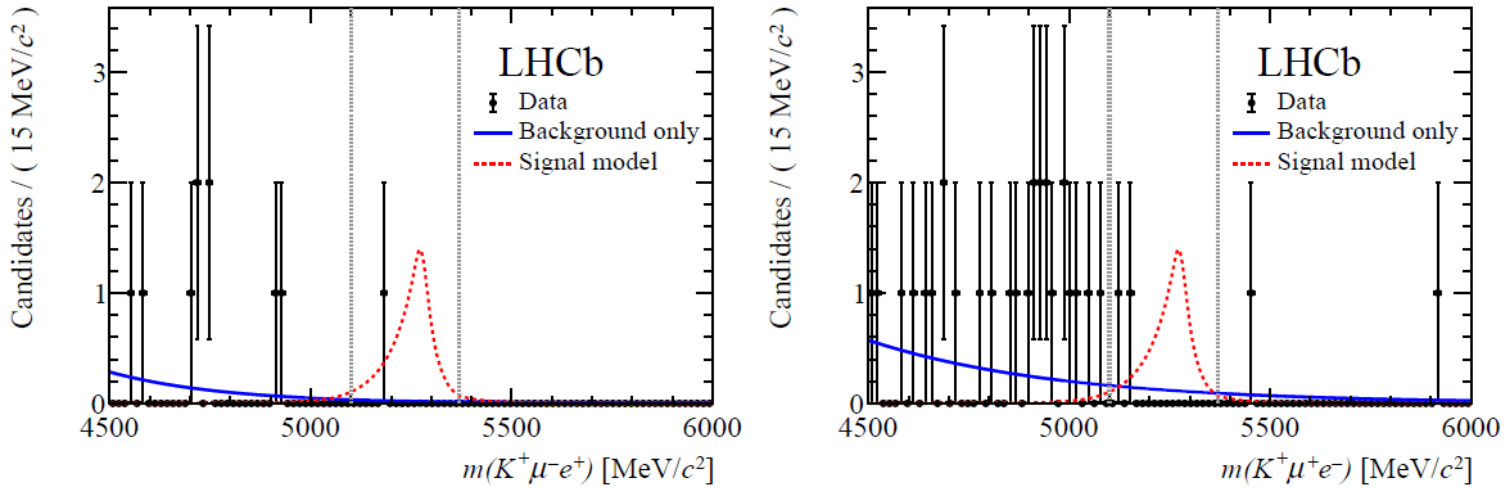
- Best limits before this measurement by BaBar
  - $BF(B^+ \to K^+\mu^- e^+) < 9.1 \times 10^{-8}$ @ 90% CL
  - $BF(B^+ \to K^+\mu^+ e^-) < 13 \times 10^{-8}$ @ 90% CL
- Branching fractions in the range $10^{-8} - 10^{-10}$ in models with Z' or leptoquarks.

- Run 1 dataset (3 fb^{-1})
- $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ and $B^+ \to J/\psi(\to e^+e^-)K^+$ used as control channels
- Background rejection:
  - $B^+ \to \overline{D^0} X l^+ \nu_l$, $\overline{D^0} \to K^+ Y l'^- \bar{\nu}_{l'}$ and decays with charmonia rejected with mass vetoes
  - Two multivariate classifiers used to suppress combinatorial and b-hadron decay backgrounds
  - Resulting background yield from b decays is negligible
- Phase-space model assumed for signal

  BF results can be corrected for different assumptions using efficiency maps given in the paper



Search for $B^+ \to K^+\mu^\pm e^\mp$ arXiv:1909.01010



- Signal yields converted to BF using $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$ norm. channel
- No signal found → set BF upper limits

$$BF(B^+ \to K^+\mu^-e^+) < 9.5 \times 10^{-9} \text{ @ } 95\%\ CL$$

$$BF(B^+ \to K^+\mu^+e^-) < 8.8 \times 10^{-9} \text{ @ } 95\%\ CL$$

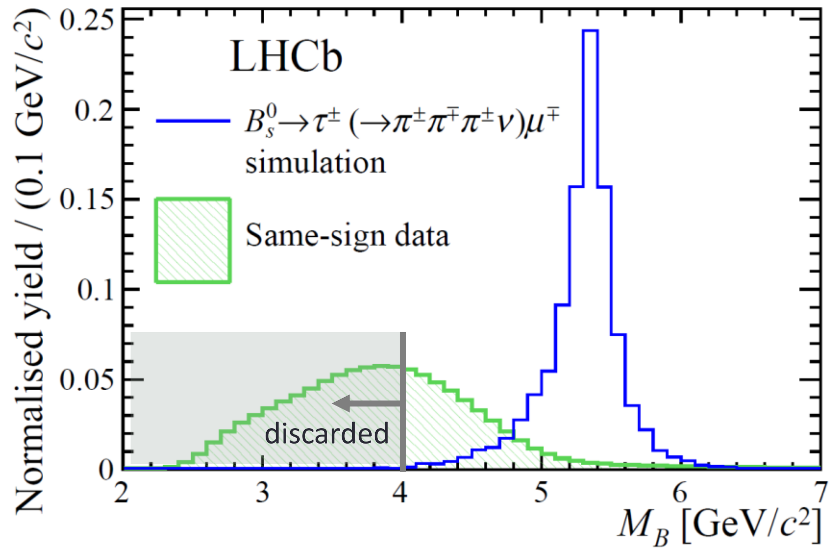
$> 10 \times$ improvement w.r.t. previous limits from BaBar

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

arXiv:1905.06614

- Exp status before this measurement
  - $BF(B^0 \to \tau^\pm\mu^\mp) < 2.2 \times 10^{-5}$ @ 95% CL BaBar
  - no limit on $BF(B^0_s \to \tau^\pm\mu^\mp)$
- Branching fractions up to 10^{-5} in models with Z' or leptoquarks.

see e.g. JHEP07 (2019) 168

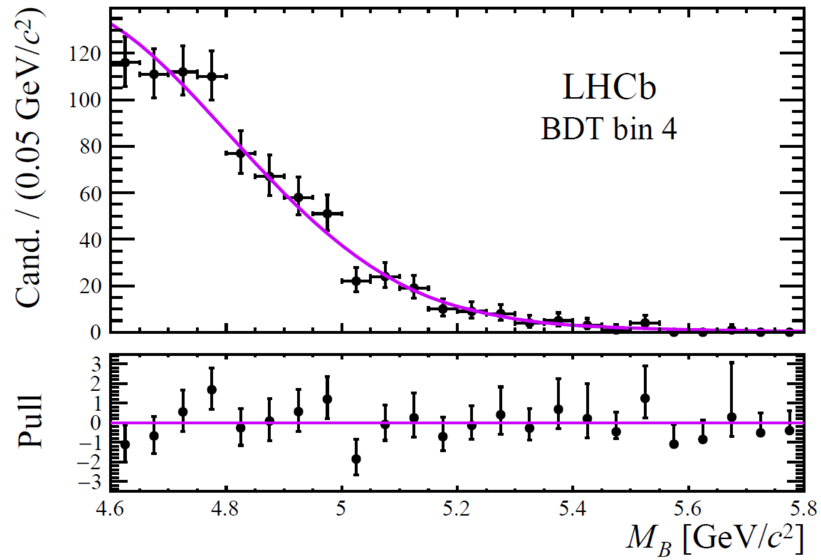


- Run 1 dataset (3 fb^{-1})
- $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ final state
  - Events from $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ also included as signal
- B mass reconstructed with 2-fold ambiguity
  - Missing momentum reconstructed through kinematic and vertex constraints
  - Solution with highest S/B is kept
- Background rejection:
  - Isolation variables to suppress decays with additional reconstructed particles
  - Multivariate classifier to suppress combinatorial background
  - $D^- \to \pi^-\pi^+\pi^-$ vetoed with $m(3\pi) < 1.8\ GeV/c^2$
  - $B^0_{(s)} \to D^-_{(s)}(\to \mu^-\nu_\mu)\pi^+\pi^-\pi^+$ suppressed based on decay time of 3π

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

arXiv:1905.06614

- Selected candidates split into 4 samples according to the output of a BDT
- Signal yield in each sample extracted through fit to the B mass
  - two fits, fixing to 0 $N^{sig}_{B^0}$ or $N^{sig}_{B^0_s}$
  - signal yields consistent with 0
- Signal yield converted to BF using $B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+$ normalisation channel



B mass fit in the lowest-background BDT bin

$$BF(\mathrm{B}^0_s \to \tau^\pm\mu^\mp) < 4.2 \times 10^{-5} \text{ @ } 95\% \; CL$$

$$BF(B^0 \to \tau^\pm\mu^\mp) < 1.4 \times 10^{-5} \text{ @ } 95\% \; CL$$

first UL for B^0_s, $\sim 2\times$ improvement w.r.t. BaBar for B^0

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

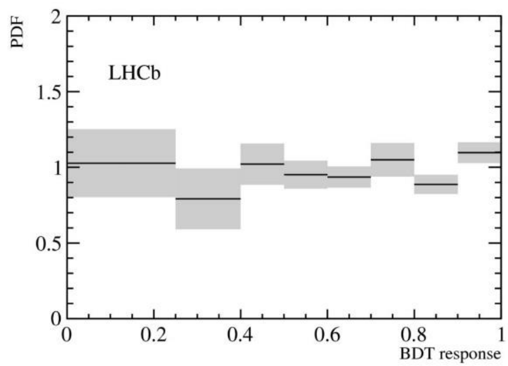
JHEP 1803 (2018) 078

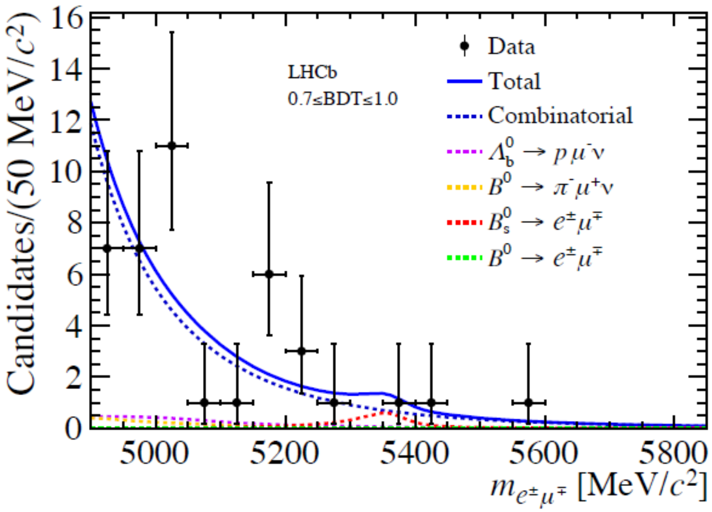
- Decay allowed in several NP scenarios including e.g. models with Z' boson, heavy singlet Dirac neutrinos, SUSY and the Pati-Salam model
- Previous best limits by LHCb based on 1 fb^{-1} Run1 data
- Updated with full Run 1 dataset (3 fb^{-1})
- Selection and analysis strategy similar to $B \to \mu\mu$
  - $B^0 \to K^+\pi^-$ and $B^+ \to J/\psi\ K^+$ used as normalisation channels
  - $B^0 \to K^+\pi^-$ also used to calibrate the signal BDT shape
- Main background from $b\bar{b} \to e^\pm\mu^\mp X$ decays
- Events in signal region consistent with the expected background:

$$BF\left(B_s^0 \to e^\pm\mu^\mp\right) < 6.3 \times 10^{-9} \text{ @ 95\% CL}$$
$$BF\left(B^0 \to e^\pm\mu^\mp\right) < 1.3 \times 10^{-9} \text{ @ 95\% CL}$$

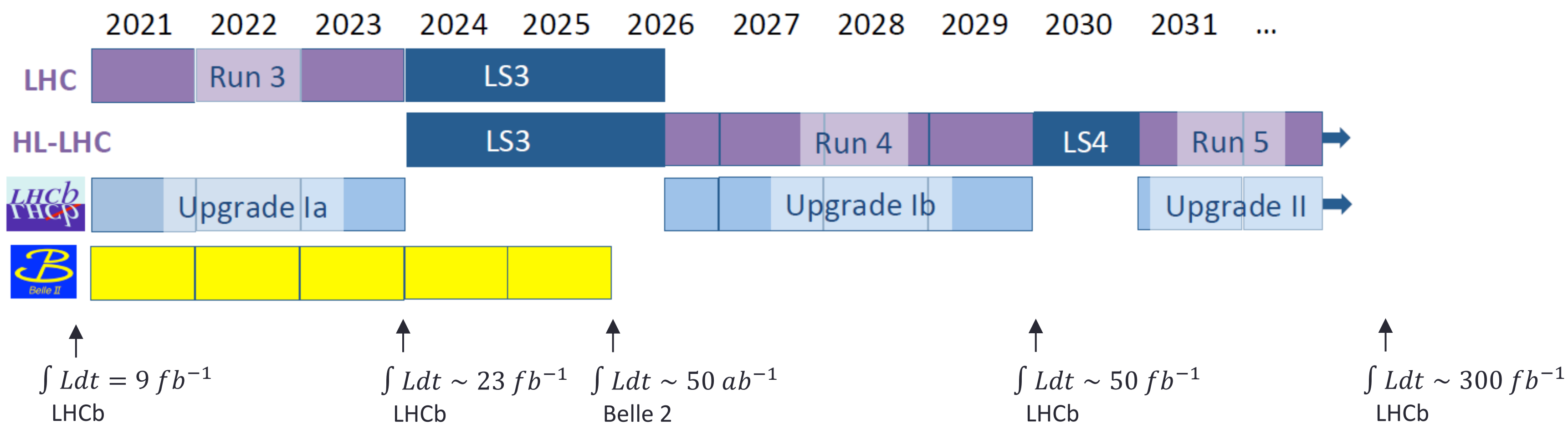
Best UL to date, improved by factor 2-3 since previous LHCb measurement

BDT shape of $B^0 \to K^+\pi^-$





Prospects for LFV decays at LHCb



	UL @ 50 fb^{-1}	UL @ 300 fb^{-1}
$B^0 \to e^\pm\mu^\mp$	2×10^{-10} [1]	9×10^{-11} [1]
$B_s^0 \to e^\pm\mu^\mp$	8×10^{-10} [1]	3×10^{-10} [1]
$B^0 \to \tau^\pm\mu^\mp$	3×10^{-6} [2]	1×10^{-6} [2]
$B^+ \to K^+e^\pm\mu^\mp$	3×10^{-10} [3]	5×10^{-11} [3]
$B^+ \to K^+\tau^\pm\mu^\mp$	$O(10^{-6} - 10^{-7})$ [4]	$O(10^{-7})$ [4]
$B^0 \to K^{*0}\tau^\pm\mu^\mp$	$O(10^{-6} - 10^{-7})$ [4]	$O(10^{-7})$ [4]
$\tau \to 3\mu$	9×10^{-9} [5]	3×10^{-9} [5]

[1] CERN-LHCb-PUB-2018-009
[2] From current limit assuming $1/\sqrt{\int Ldt}$ scaling.
[3] From current limit assuming $1/\int Ldt$ scaling (a little optimistic).
[4] From [1] assuming $1/\sqrt{\int Ldt}$ scaling.
[5] From JHEP 02 (2015) 121 assuming $1/\sqrt{\int Ldt}$ scaling.

More searches ongoing: $B^0 \to K^{*0}e^\pm\mu^\mp, \Lambda_b \to \Lambda e^\pm\mu^\mp, \ldots$.

NB: ULs @95%, except for $\tau \to 3\mu$ @90%

Summary

- Intense effort in LHCb to search for non-SM effects in rare and forbidden decays, including $B \to l^+ l^-$ and LFV B decays
  - First single-experiment observation of $B_s^0 \to \mu^+\mu^-$ and first lifetime measurement, no evidence of $B^0 \to \mu^+\mu^-$ yet
  - Best upper limits on a number of rare or LFV decays, including $B_{(s)}^0 \to \tau\tau$, $B \to \tau\mu$, $B \to e\mu$, $B \to Ke\mu$
- Results consistent with SM. But…
  - … all measurements presented today will be updated on full Run 2 dataset (6 fb^{-1}, 13 TeV ➔ $> 3 \times B$ sample of Run 1)
  - Ongoing work on additional channels
- The imminent upgrade-I phase will allow a significant jump in sensitivity in the search for physics signals beyond the SM

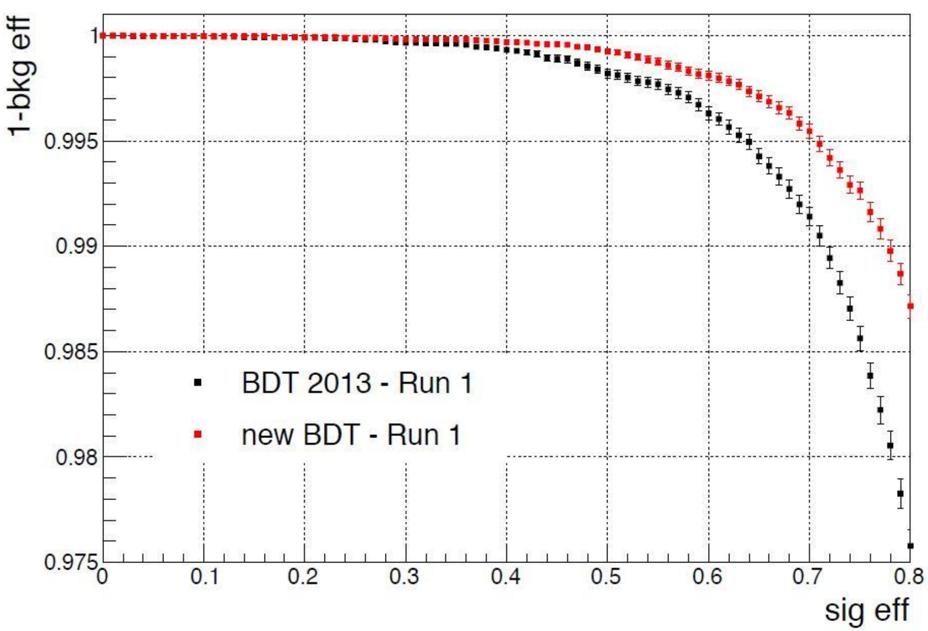
BACKUP

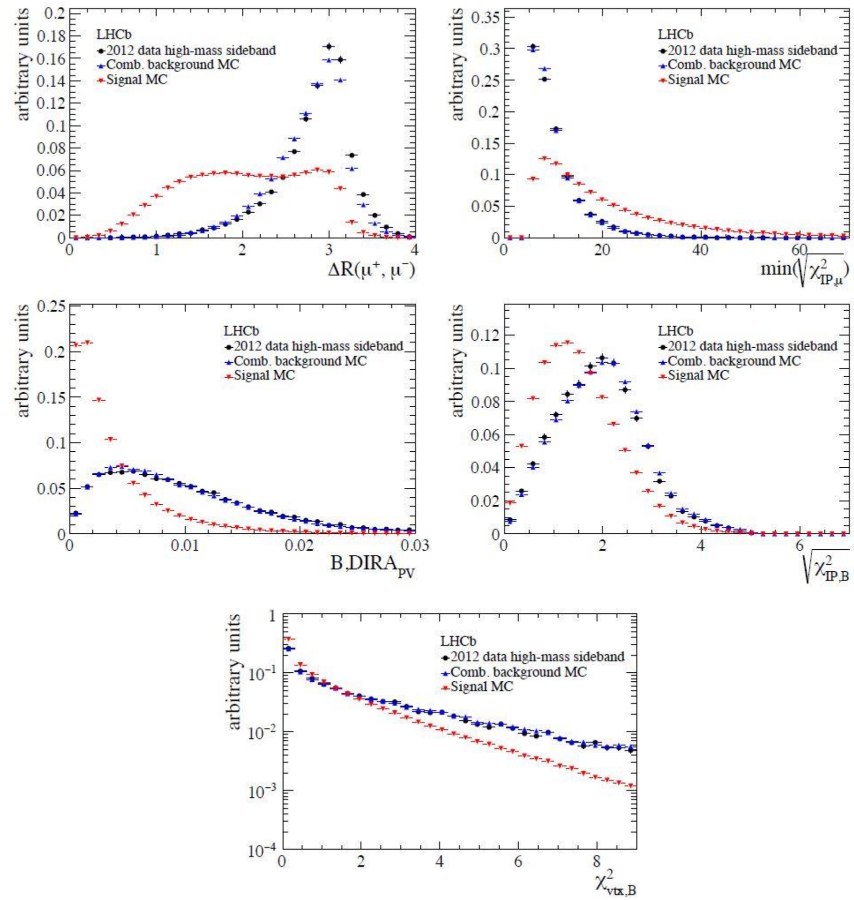
$B \to \mu\mu$ multivariate classifier (BDT)

PRL 118, 191801 (2017)

- Long track isolation used as starting point to build the global BDT classifier
- Optimisation and training on MC
- Correlation with $m_{\mu\mu}$ below 5%
- Compared to prev analysis: -50% comb background with same signal efficiency

7 input variables: 2 track isolations + the 5 quantities shown below





$B^+ \to K^+\mu^\pm e^\mp$ systematic uncertainties

arXiv:1909.01010

Effect	$B^+ \to K^+\mu^+e^-$	$B^+ \to K^+\mu^-e^+$
Data-simulation corrections	1.0%	1.0%
Electron-muon differences	1.4%	1.4%
Fitting model	2.1%	2.1%
PID resampling	4.5%	5.5%
Trigger	1.0%	1.0%
Normalisation factor	3.5%	3.5%
Total	6.4%	7.1%
Background	0.60	0.43