Searches for Lepton Flavour Violating decays at LHCb

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EPS-HEP / Flavour Physics and CP Violation
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Introduction

- Conservation of the lepton number is well-established ($\mu \to e\gamma$, $\mu \to 3e$...) but accidental in the theory
- Oscillations of massive neutrinos demonstrate LFV occurs for neutrals, can mediate charged LFV in loops with BF~10^{-50} : beyond experimental reach
- Recent hints of deviation from LFU in semileptonic B decays (R_K, R_{K^*}, R_D, R_{D^*}...) strongly motivate searches for LFV decays [Glashow, Guadagnoli, Lane, Phys. Rev. Lett. 114, 091801]
- NP models like Z' or LQ foresee BF enhancements to levels accessible at LHC: probe massive particles beyond the reach of direct searches

Interesting correlations between observables in some LQ models

[ArXiv: 1609.08895]

$$\begin{cases} \dfrac{\mathcal{B}(B_s \to \mu^+ e^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM}} \sim 0.01 \left(\dfrac{1-R_K}{0.23}\right)^2 \\[2ex] \dfrac{\mathcal{B}(B_s \to \tau^+(e^-,\mu^-))}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM}} \sim 4 \left(\dfrac{1-R_K}{0.23}\right)^2 \\[2ex] \mathcal{B}(B \to K(e^\pm,\mu^\pm)\tau^\mp) \sim 2\cdot 10^{-8} \left(\dfrac{1-R_K}{0.23}\right)^2 \end{cases}$$

- Will report here 3 recent measurements from LHCb:

  1. $B \to e^\pm \mu^\mp$ 2. $B \to \tau^\pm \mu^\mp$ 3. $B^+ \to K^+ e^\pm \mu^\mp$

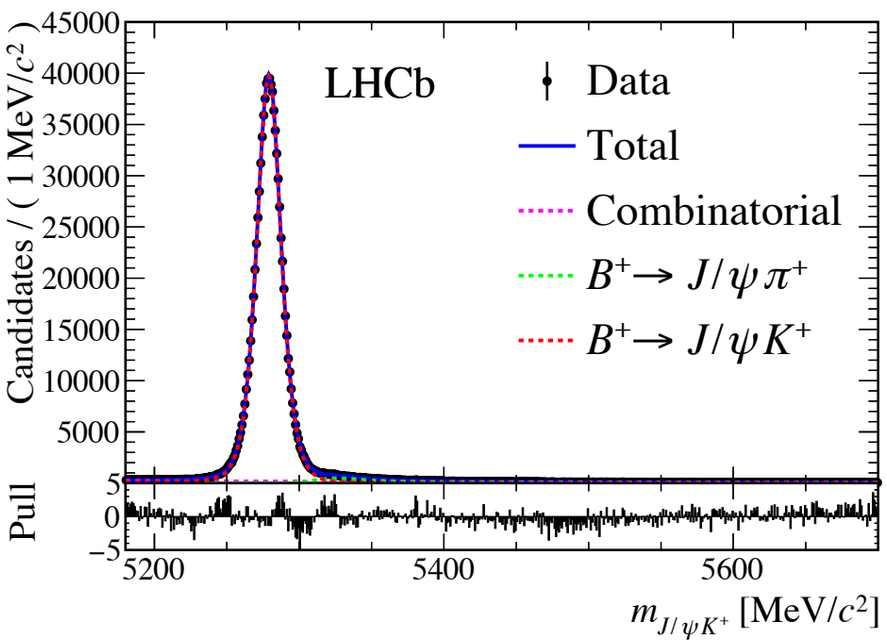
  using Run 1 data sample: 1 fb^{-1} ($\sqrt{s}$=7 TeV) + 2 fb^{-1} ($\sqrt{s}$=8 TeV)

$B_{d,s} \to e\,\mu$ / selection and normalisation [JHEP 1803 (2018) 078]

- Trigger on high-p_T muon or high-E_T electron
- Event selection based on electron and muon tracks (identified via PID criteria) forming a displaced vertex

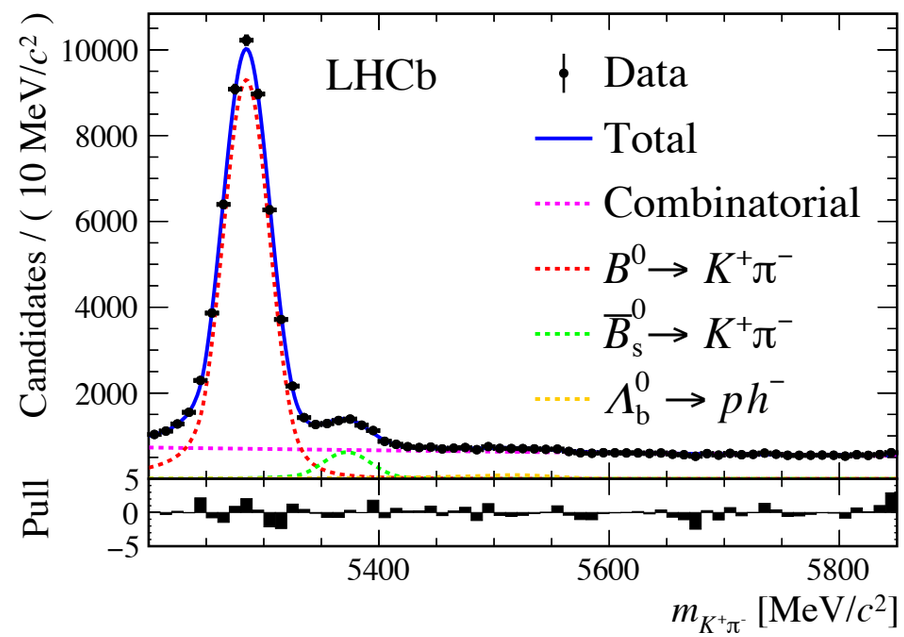
To measure the BF, the signal events are normalised by means of two known channels:

1. $B^+ \to J/\psi(\mu^+\mu^-)K^+$



- Large yield, similar trigger to the signal

2. $B_d \to K^+\pi^-$



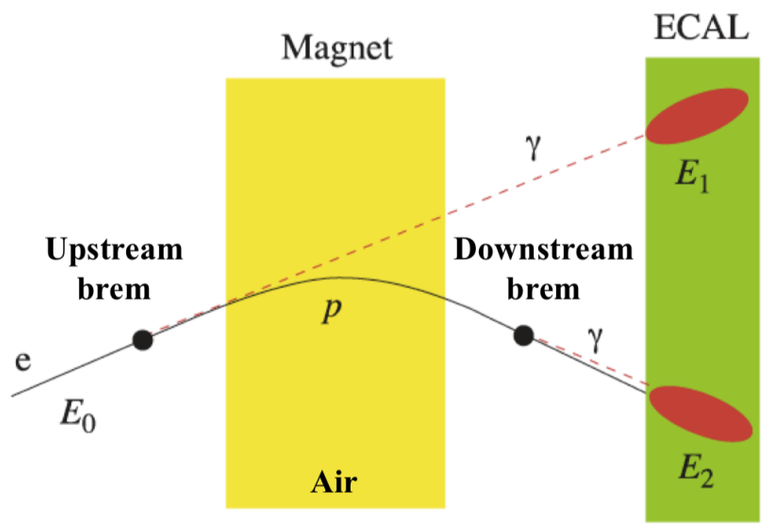
- Similar reconstruction to the signal

Efficiencies for signal and normalisation modes are taken from MC with the exception of PID and trigger, which are obtained from high-purity data calibration samples

$B_{d,s} \to e\,\mu$ / bremsstrahlung

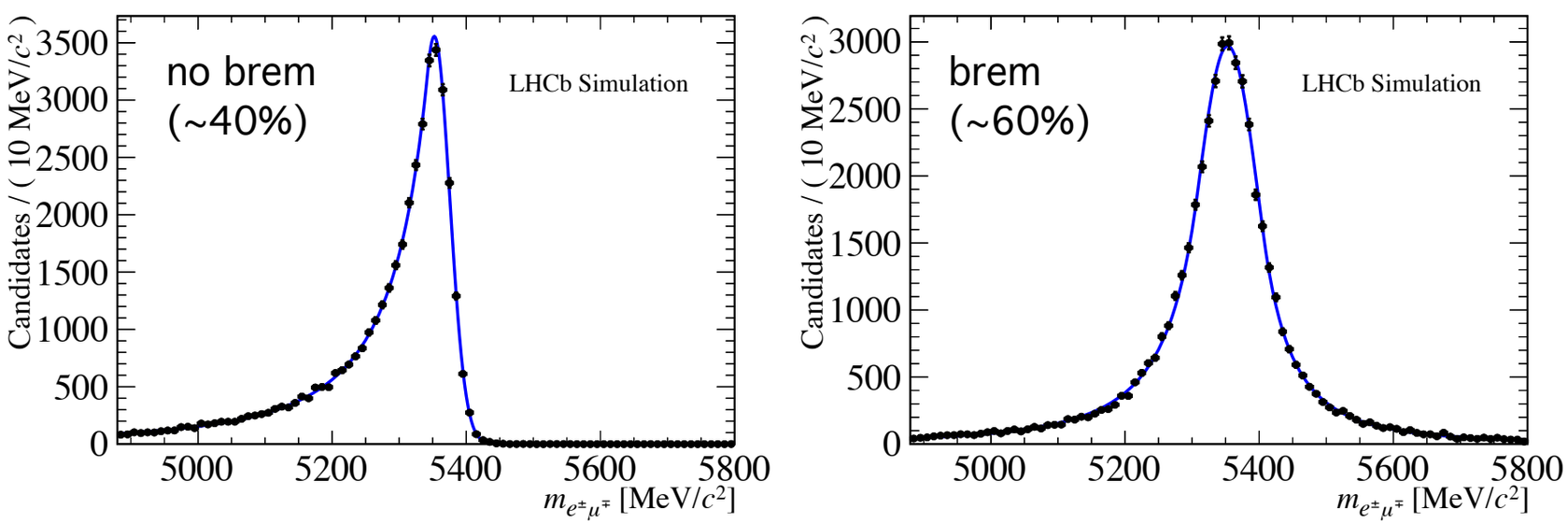
[JHEP 1803 (2018) 078]

Electrons emit significant bremsstrahlung photons at LHCb: to improve the momentum resolution, a photon cluster in the calorimeter is searched for



If found, the photon energy is added back to the electron

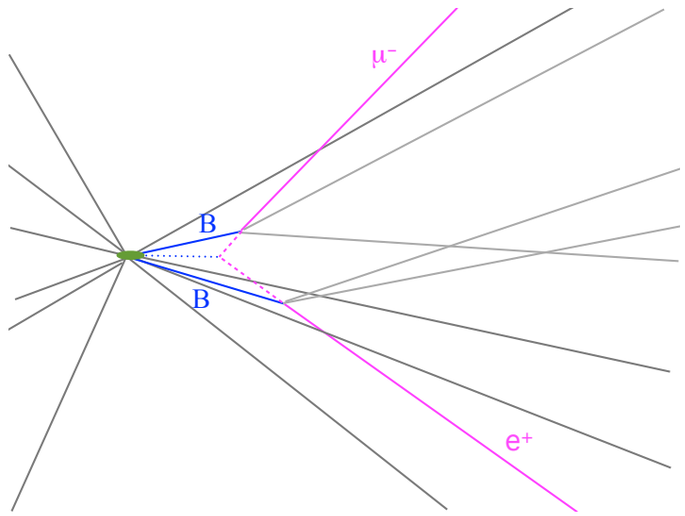
Selection efficiencies and mass shapes depend on wether or not the bremsstrahlung is recovered:



The two event categories are analysed separately.

$B_{d,s} \to e\,\mu$ / backgrounds

[JHEP 1803 (2018) 078]



1. Combinatorial background is rejected by means of a topological BDT, trained on signal MC vs same-sign data and calibrated on $B \to K\pi$ data (proxy for the signal)

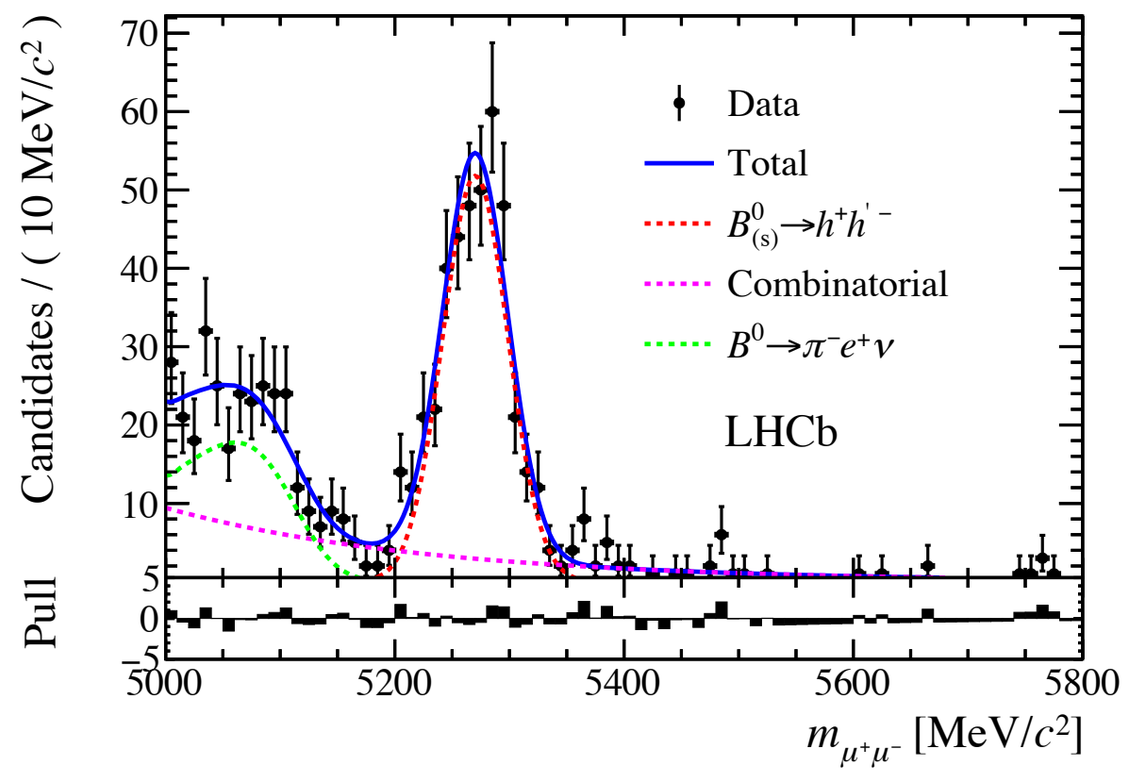
- Data are categorised in 8 bins in the BDT response to maximise the sensitivity

2. $B \to hh$ ($h=K,\pi$) with two misidentified hadrons peaks under the B_d signal

Two independent estimates:

1. Normalised to $B \to J/\psi K^+$
2. From $B \to hh \to \pi e$ data (single misID)

~0.1 event survive the PID selection

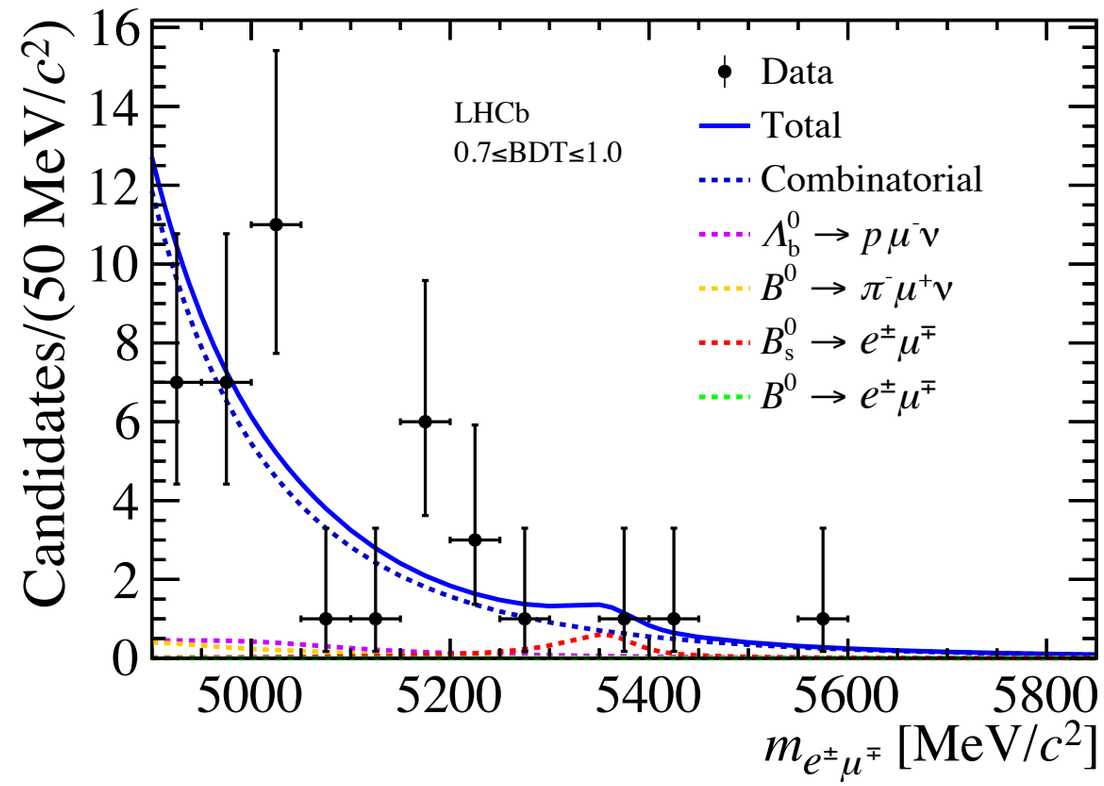


3. $B_d \to \pi\mu\nu$ and $\Lambda_b \to p\mu\nu$ with $\pi,p \to e$ misID are found to be sizeable (on the lower mass region) and included in the mass fit

$B_{d,s} \to e\,\mu$ / results

[JHEP 1803 (2018) 078]

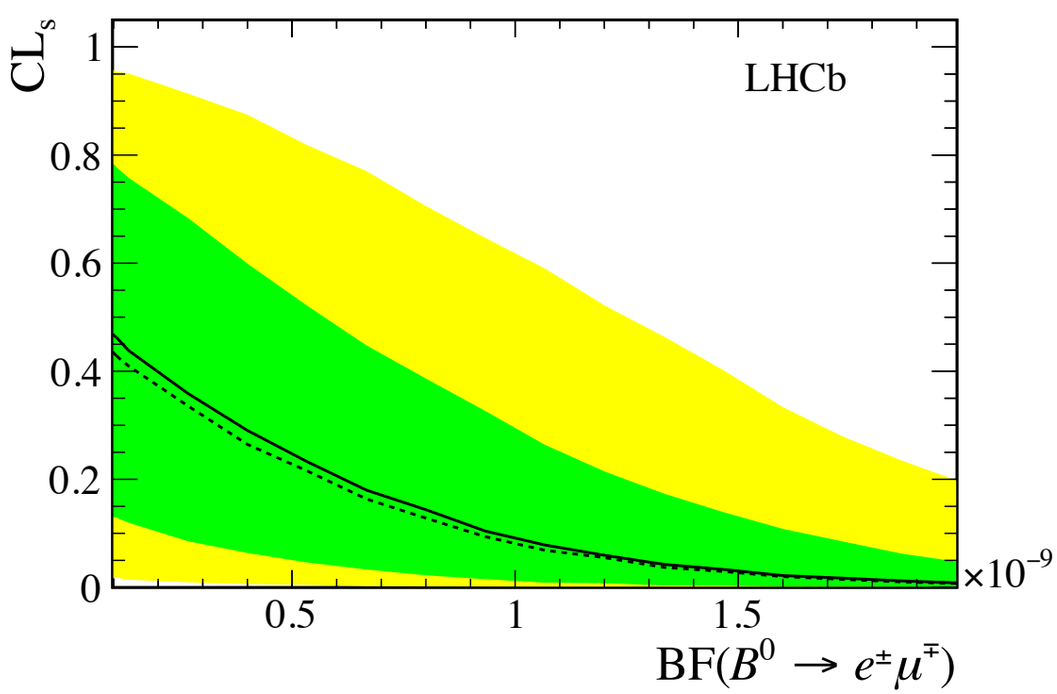
The BF is extracted with a simultaneous invariant-mass fit to the bremsstrahlung categories and BDT bins.

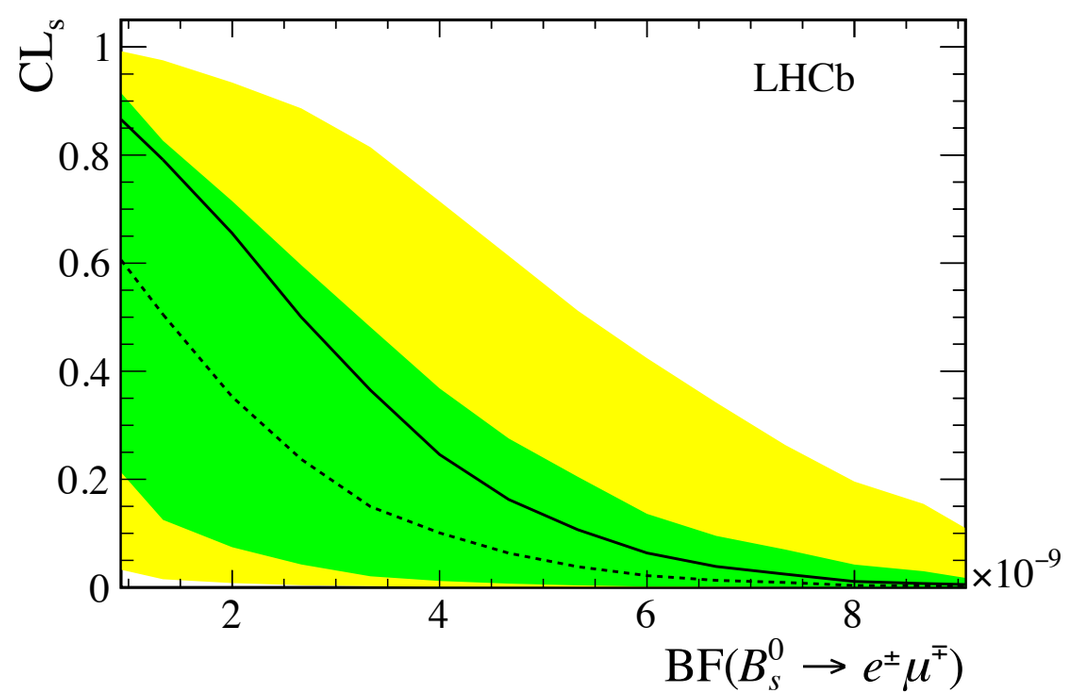


No excess in the signal region, set a limit with the CL_s method at 95% (90%) C.L.:

$$\mathcal{B}(B^0 \to e^\pm\mu^\mp) < 1.3\,(1.0) \times 10^{-9}$$
$$\mathcal{B}(B_s^0 \to e^\pm\mu^\mp) < 6.3\,(5.4) \times 10^{-9}$$

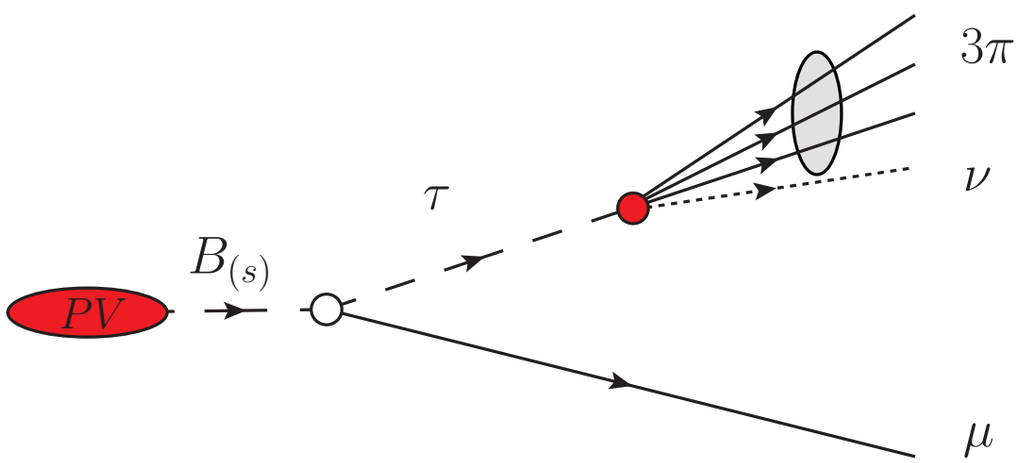
which supersedes the previous best limit (LHCb 1 fb^{-1}) [PRL 111 (2013) 141801]



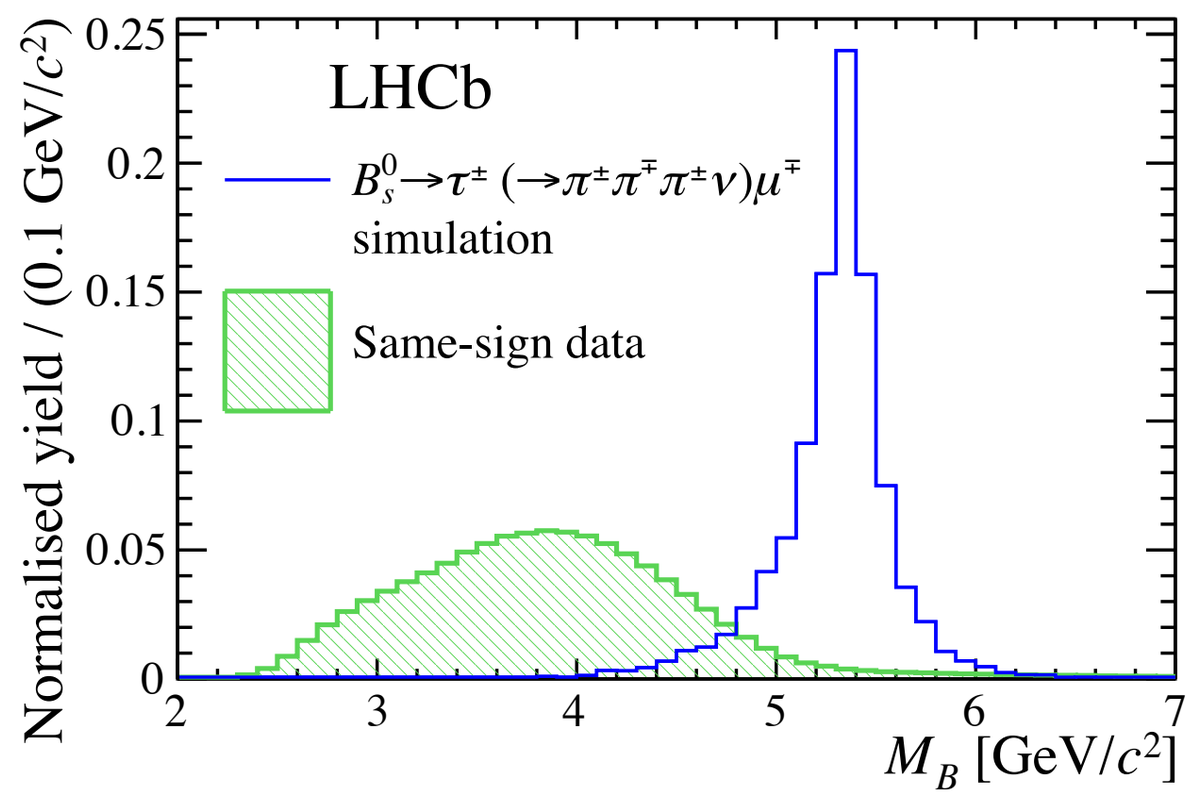


$B_{d,s} \to \tau\,\mu$ / selection and normalisation [ArXiv:1905.06614]

- Trigger on high-p_T muon
- The muon is combined with an oppositely charged τ (reconstructed in 3πν) to form a displaced vertex
- Normalisation channel with similar topology: $B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$
- Same-sign data are employed to model the background



Kinematic constraints allow to compute the B mass analytically with a two-fold ambiguity. The solution with the highest S/B is kept (M_B).



Only candidates with M_B > 4 GeV are retained

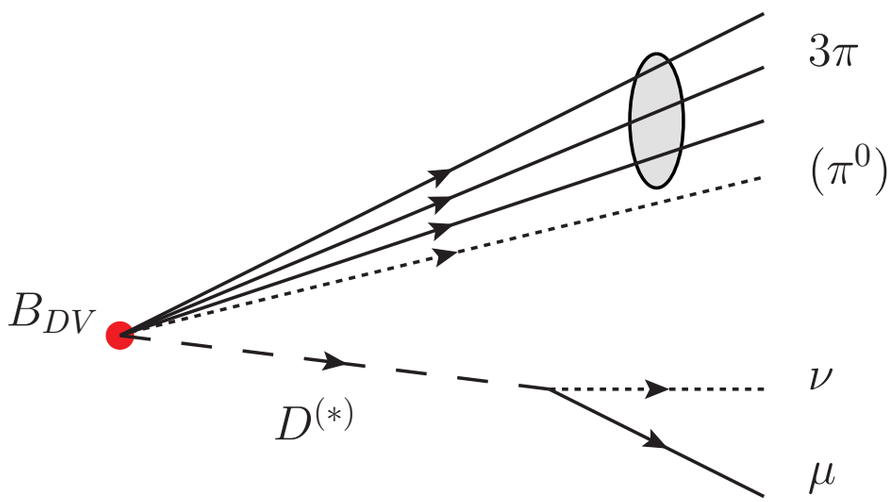
$B_{d,s} \to \tau\,\mu$ / backgrounds

[ArXiv:1905.06614]

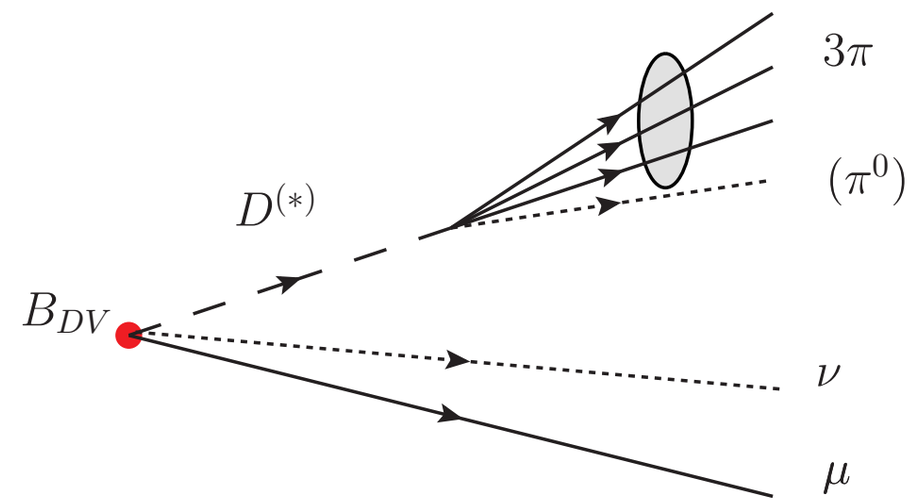
- Cut-based preselection reduces the dataset while keeping ~100% signal efficiency
- Isolation criteria are applied to reject backgrounds with extra tracks

Two background components survive the selection:

1. Partially reconstructed, two topologies:



reduced to ~0 with a cut on the τ decay time



sizeable, included in the fit

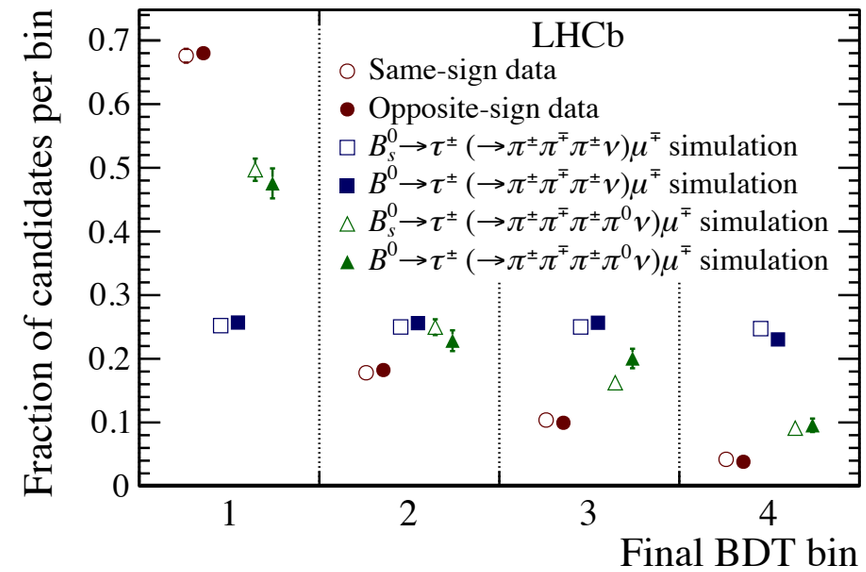
2. Combinatorial

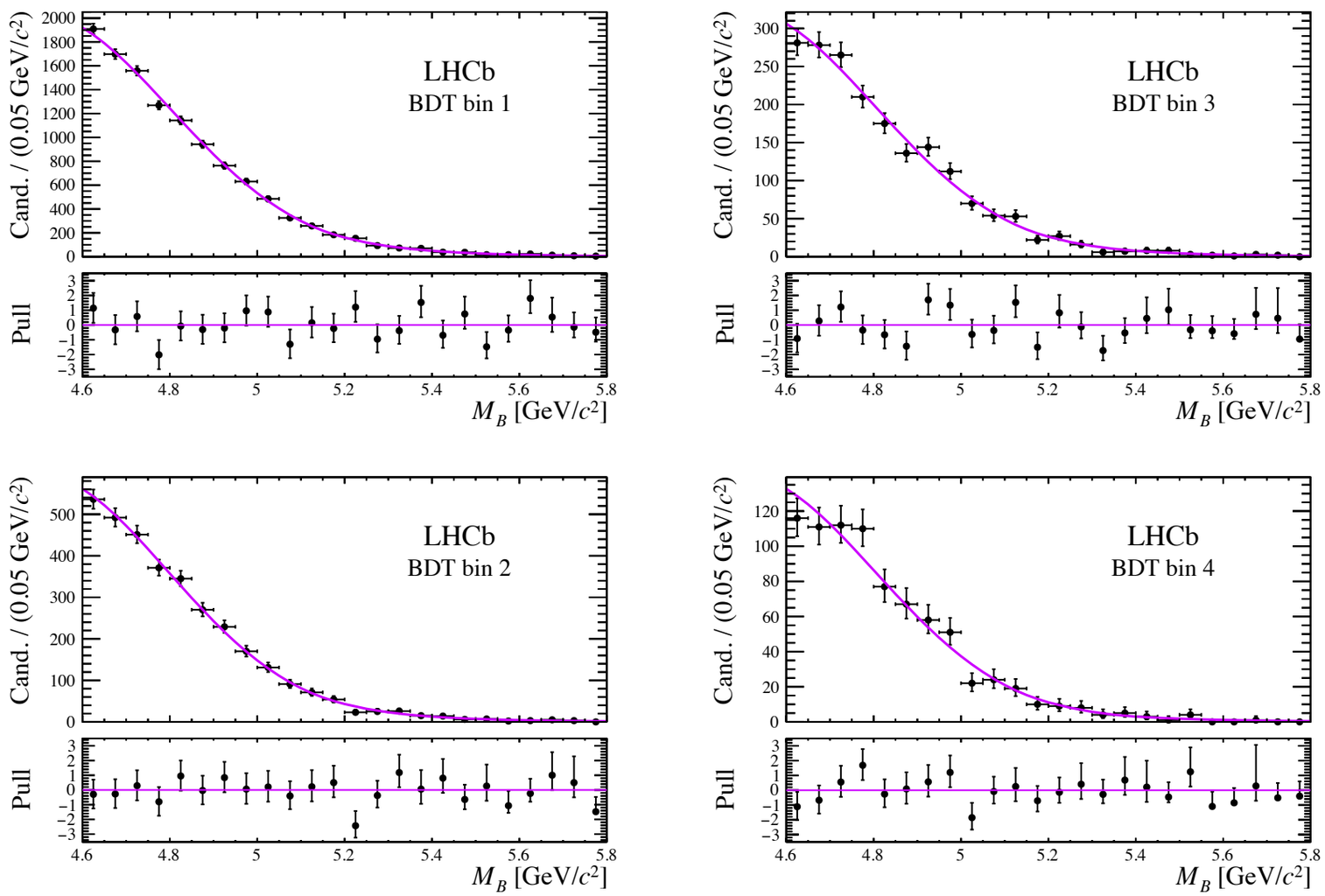
A BDT is trained on signal MC vs upper mass sideband (>6.2 GeV) of SS data

$B_{d,s} \to \tau\,\mu$ / mass fits

[ArXiv:1905.06614]

- A Final BDT trained on MC vs SS data (full mass range) is used to categorise the events
- BDT signal distribution is flattened, while background reduces at high BDT values
- Events in 4 BDT bins are simultaneously fitted





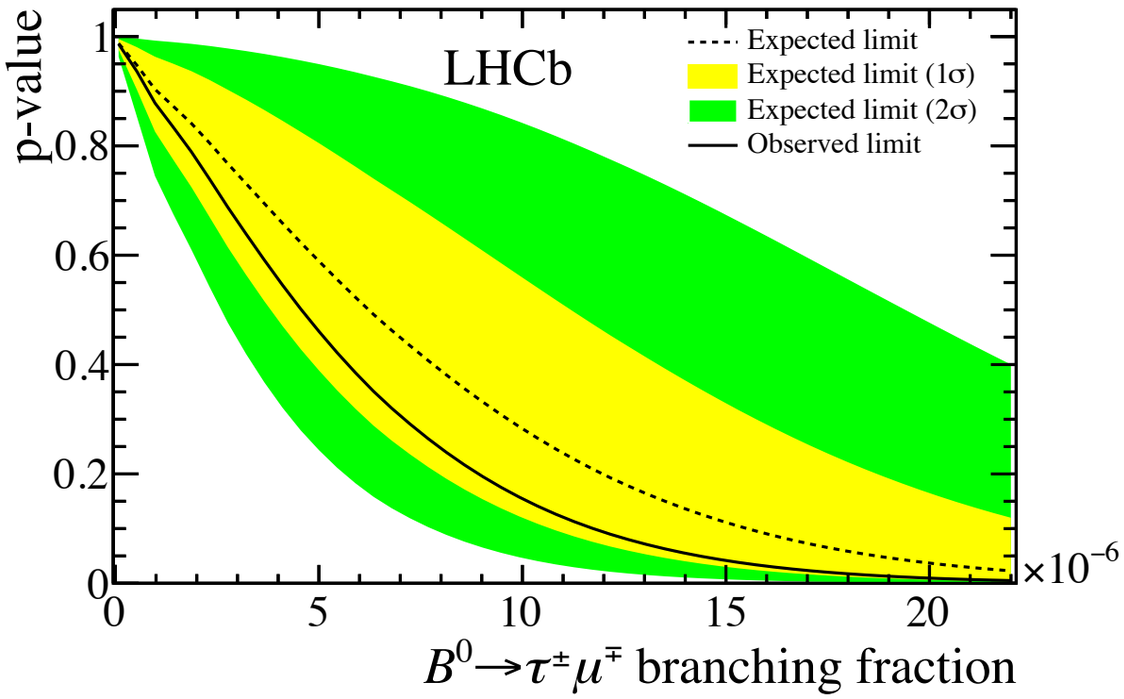
$B_{d,s} \to \tau\,\mu$ / results

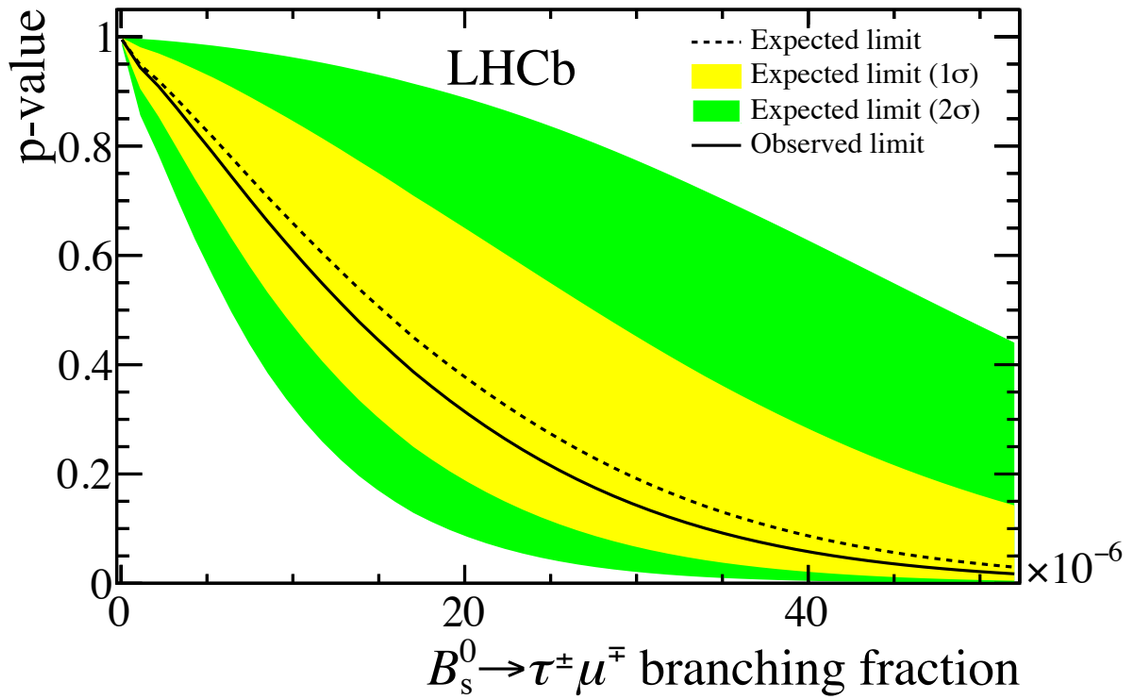
[ArXiv:1905.06614]

- No presence of signal, limit with CL_s method at 95% CL:

$$\mathcal{B}\left(B^0 \to \tau^\pm \mu^\mp\right) < 1.4 \times 10^{-5} \qquad \text{(assuming no } B_s \text{ signal)}$$
$$\mathcal{B}\left(B^0_s \to \tau^\pm \mu^\mp\right) < 4.2 \times 10^{-5} \qquad \text{(assuming no } B_d \text{ signal)}$$

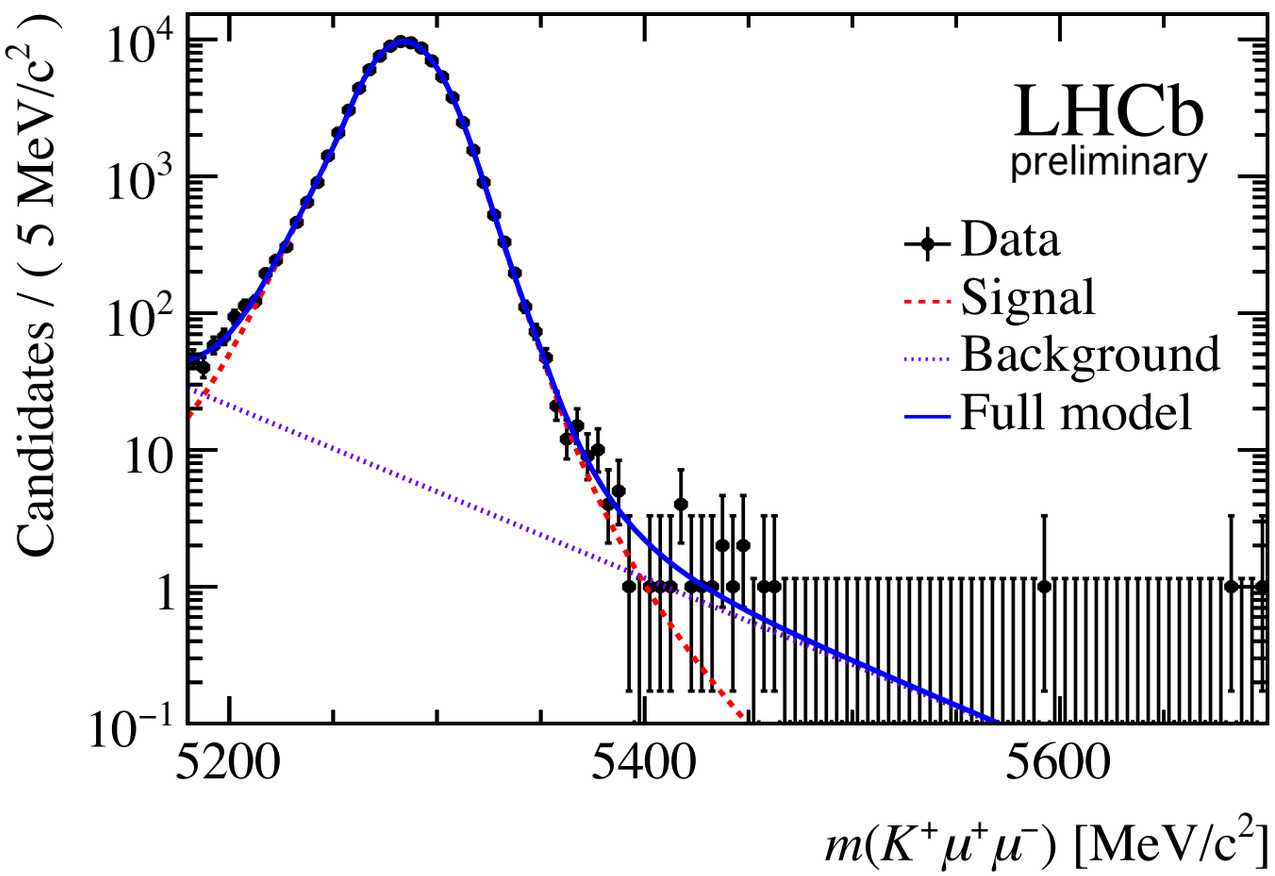
- B_d limit improves by a factor of 2 BaBar's result [Phys. Rev. D77 (2008) 091104]
- First limit on the B_s mode





$B^+ \to K^+ e \mu$ / selection and normalisation [LHCB-PAPER-2019-022]

- Trigger on high-p_T muon
- K, e and μ tracks must originate from a common, displaced vertex



- Normalisation channel with similar topology: $B^+ \to J/\psi(\mu^+\mu^-)K^+$
- Same selection applies to the normalisation channel + m(μ+μ-) must be consistent with the J/ψ mass

- Simulated samples needed for efficiencies are corrected from data concerning B production kinematics, vertex quality, detector occupancy and PID

$B^+ \to K^+ e \mu$ / backgrounds

[LHCB-PAPER-2019-022]

1. Partially reconstructed, most abundant are double semileptonic: $B^+ \to \overline{D}^0(\to K^+ Y l^- \overline{\nu}_l) X l^+ \nu_l$

   Rejected by requiring $m(K^+l^-)>1885$ MeV

2. Decays via charmonium resonances with lepton misidentification, e.g. $B^+ \to J/\psi(l^+l^-)K^+$

   Rejected via mass vetoes

3. Combinatorial background

   Reduced with a dedicated BDT algorithm exploiting the event topology and isolation, trained on signal MC vs upper mass data sideband

4. Fully (partially) reconstructed B decays with at least one misidentificated particle
   e.g. $B^+ \to K^+ l^+ l^-$ $(B^0 \to K^* l^+ l^-)$

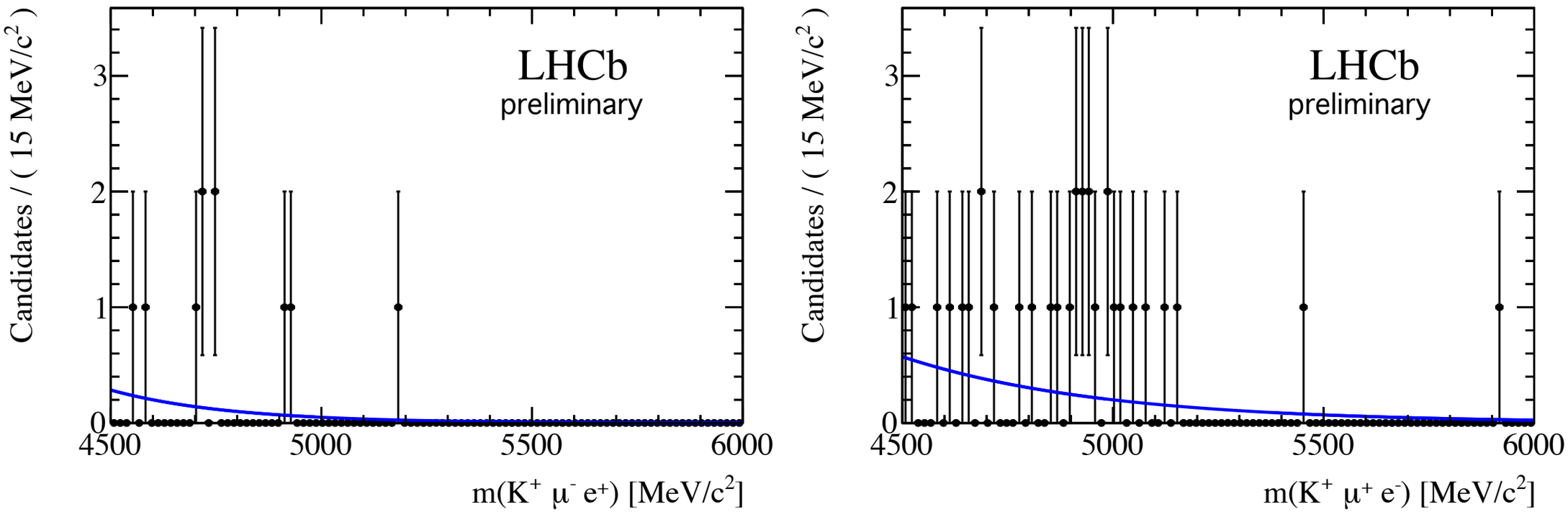
   Rejected by means of PID cuts + dedicated BDT, trained on signal MC vs lower mass data sideband

Each background contamination is estimated from MC, normalising to $B^+ \to J/\psi(\mu^+\mu^-)K^+$

$B^+ \to K^+ e \mu$ / results

[LHCB-PAPER-2019-022]

- Signal shape is modelled from MC separately in two bremsstrahlung categories, and corrected with differences observed in $B^+ \to J/\psi(\mu^+\mu^-, e^+e^-)K^+$ data
- Single exponential shape for the combinatorial background
- The two lepton charge combinations are measured separately



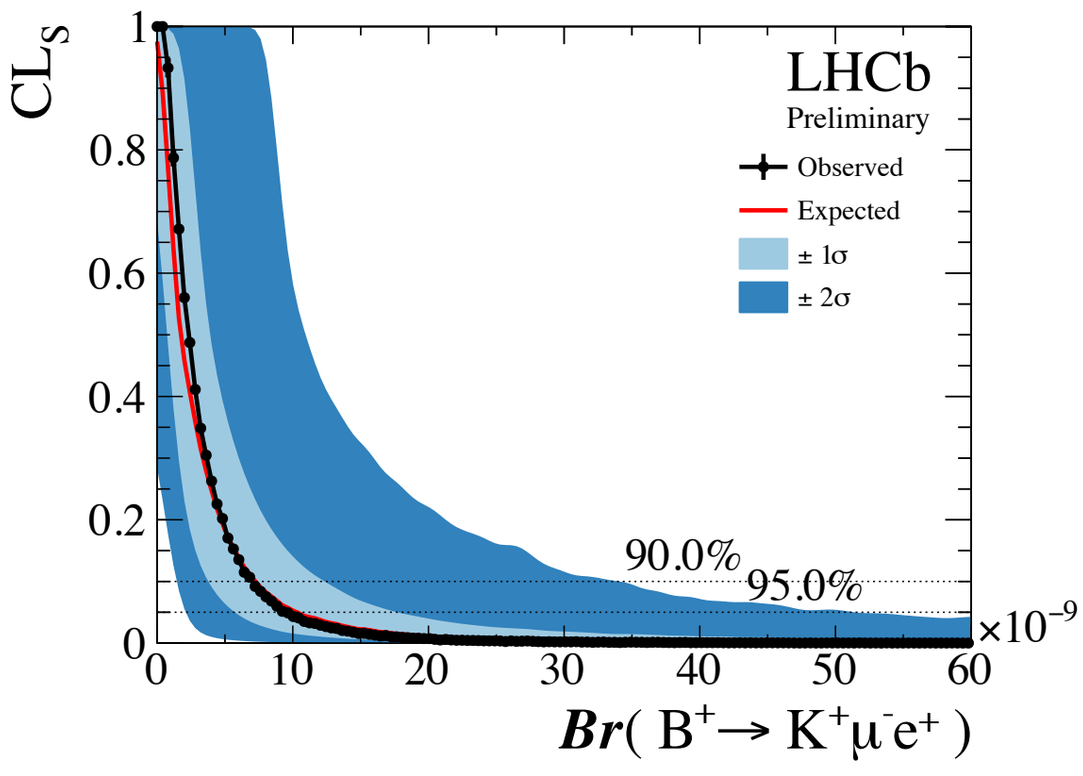
$B^+ \to K^+ e \mu$ / results

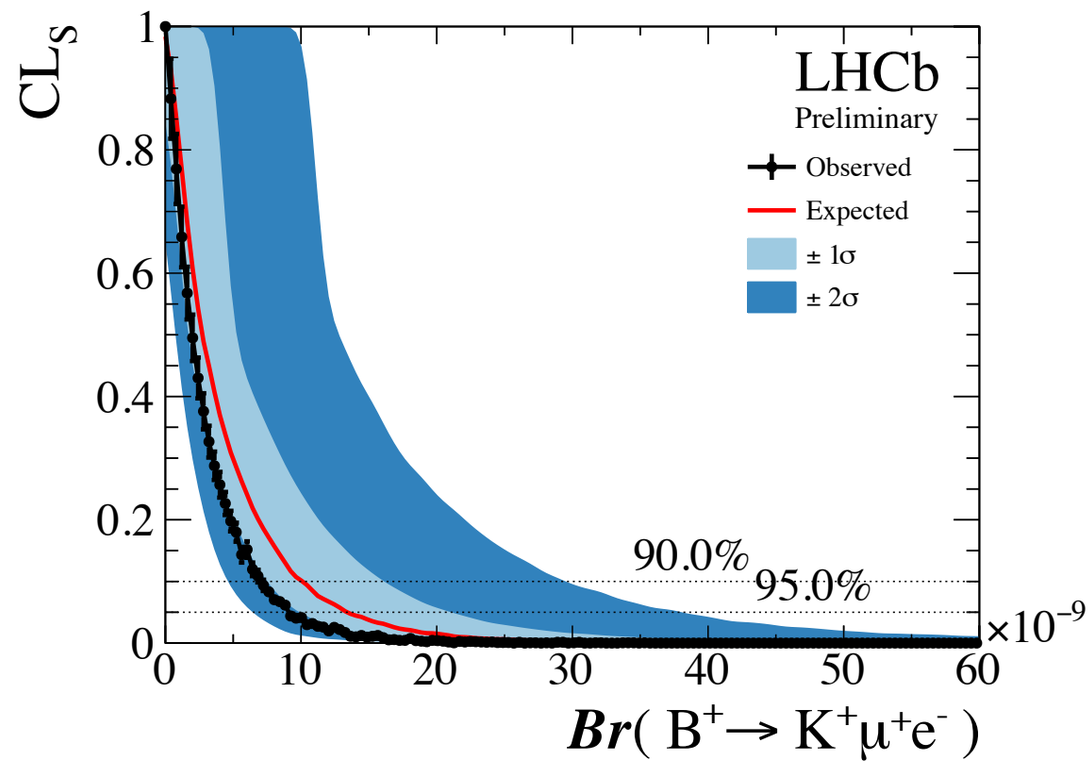
[LHCB-PAPER-2019-022]

- No presence of signal: a limit on the BF is set according to the CL_s prescription

$\mathcal{B}/10^{-9}$	90% C. L.	95% C. L.
$B^+ \to K^+ \mu^- e^+$	7.0	9.5
$B^+ \to K^+ \mu^+ e^-$	7.1	9.1

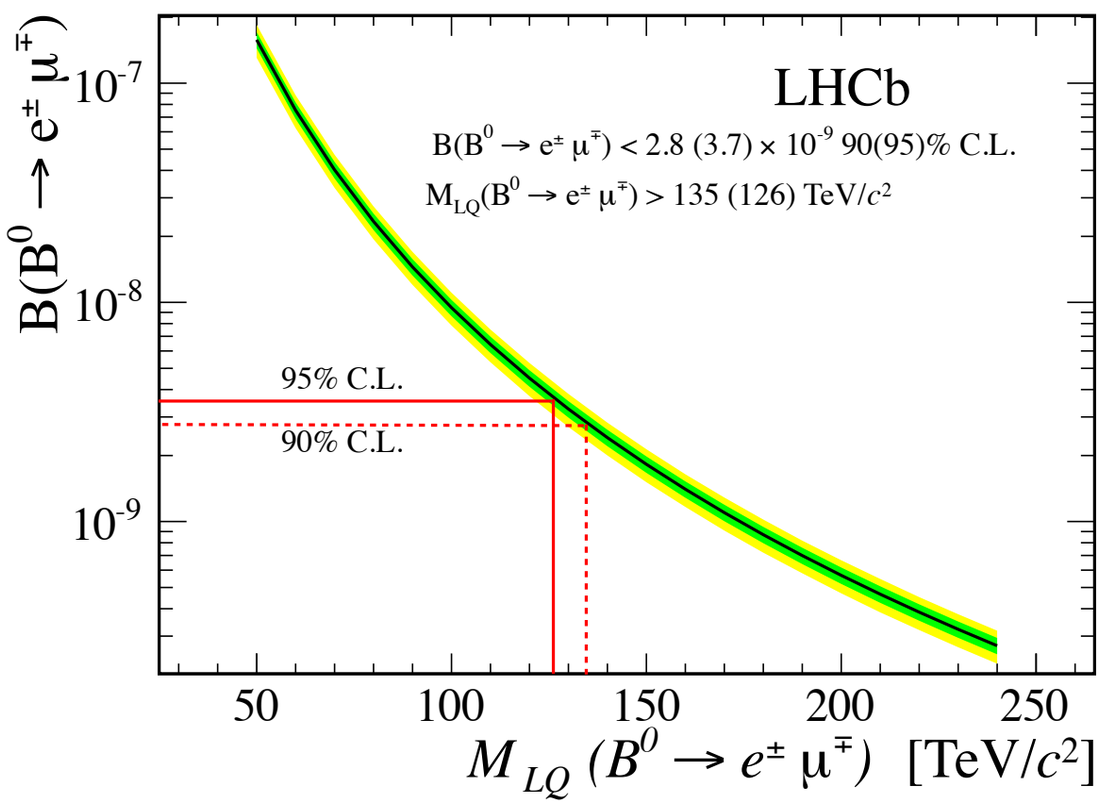
- Previous best limits from BaBar are improved by more than an order of magnitude





Conclusions

- Hints of lepton non-universality in b decays demand searches for LFV decays
- LHCb is currently dominating the scene, with Belle II to join on some channels
- 3 recent results presented here provide strong constraints to NP models with Run 1 data
- LQ models being pushed to M > 120 TeV

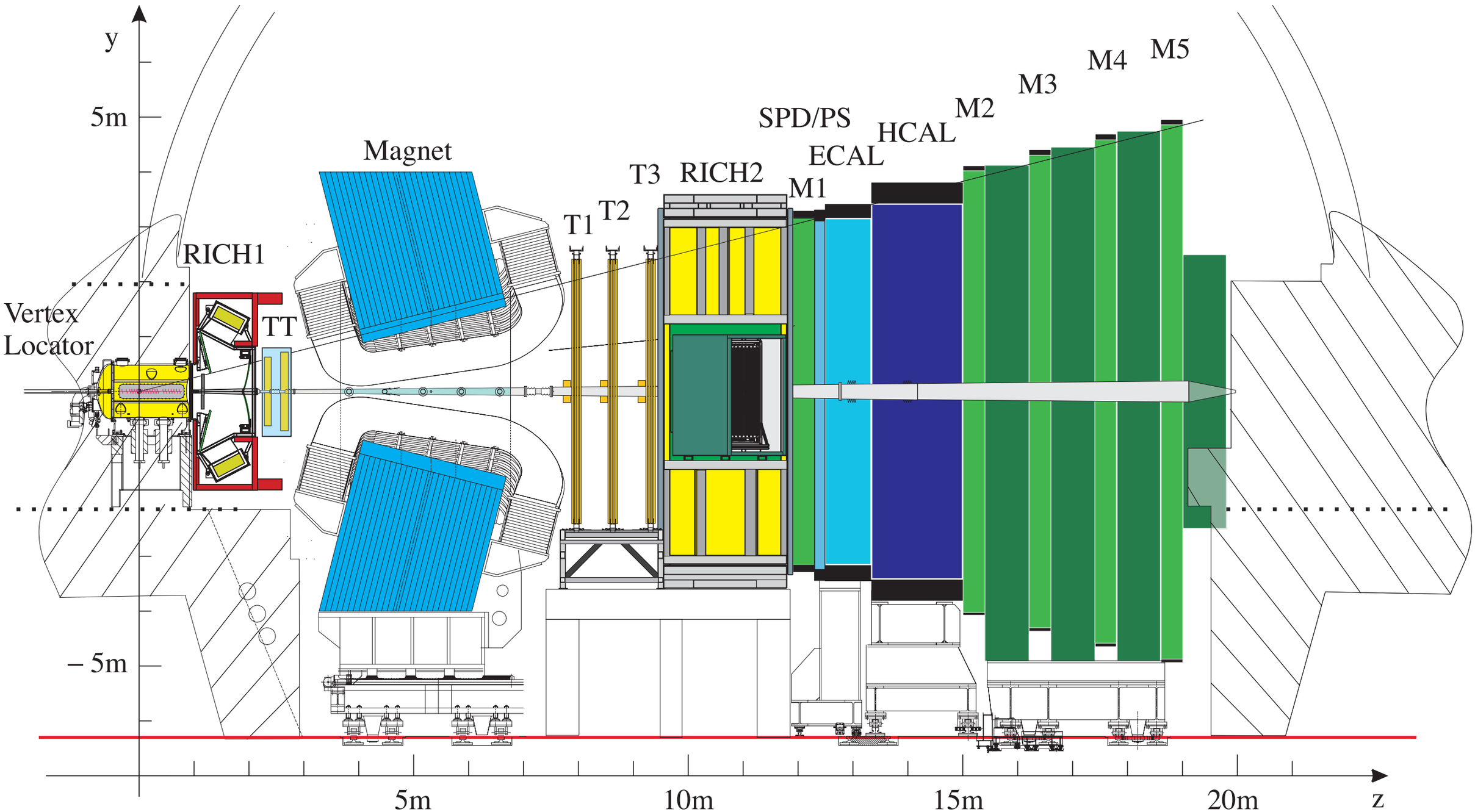


- Many more LFV measurements being performed at LHCb, not only on B decays
- Run 2 ($6 fb^{-1}$ at $\sqrt{s}$ = 13 TeV) data have ~ 4 x B candidates with respect to Run 1!

backup

The LHCb detector

JINST 3 (2008) S08005



$B_{d,s} \to e\,\mu$ / additional material

[JHEP 1803 (2018) 078]

The BF is measured with respect to normalisation channels to remove some systematic errors

$$\mathcal{B}(B^0_{(s)} \to e^\pm \mu^\mp) = \sum_i w^i \frac{\mathcal{B}^i_{\rm norm}}{N^i_{\rm norm}} \frac{\varepsilon^i_{\rm norm}}{\varepsilon_{\rm sig}} \frac{f_q}{f_{d(s)}} \frac{\mathcal{L}^i_{\rm norm}}{\mathcal{L}_{\rm sig}} \times N_{B^0_{(s)} \to e^\pm \mu^\mp}$$

weights proportional to BF and yield

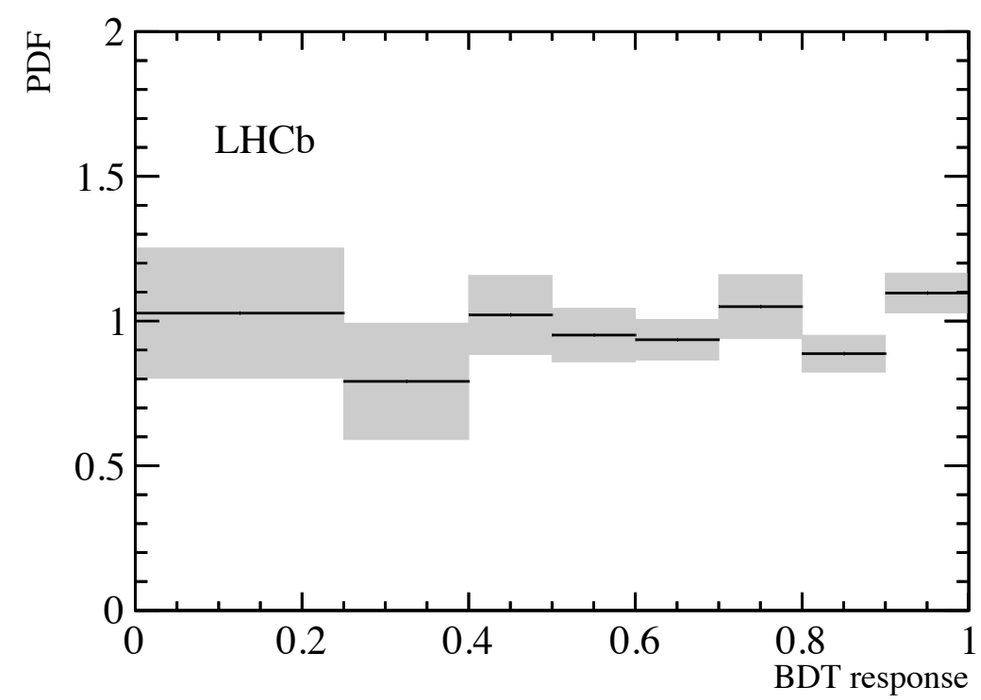
normalisation/signal efficiency ratio

hadronisation ratio

The correctness of the normalisation procedure is validated by measuring:

$$R_{\rm norm} = \frac{N_{B^0 \to K^+\pi^-} \times \varepsilon_{B^+ \to J/\psi K^+}}{N_{B^+ \to J/\psi K^+} \times \varepsilon_{B^0 \to K^+\pi^-}} = 0.332 \pm 0.002\,({\rm stat}) \pm 0.020\,({\rm syst})$$

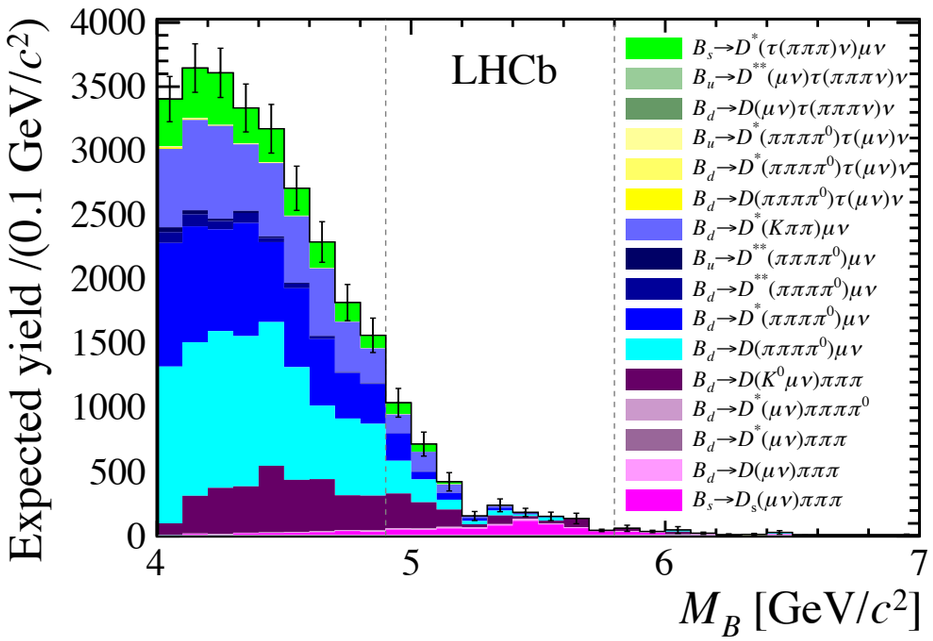
BDT calibration is performed on $B \to K\pi$ data, triggered independently of the signal presence (TIS)



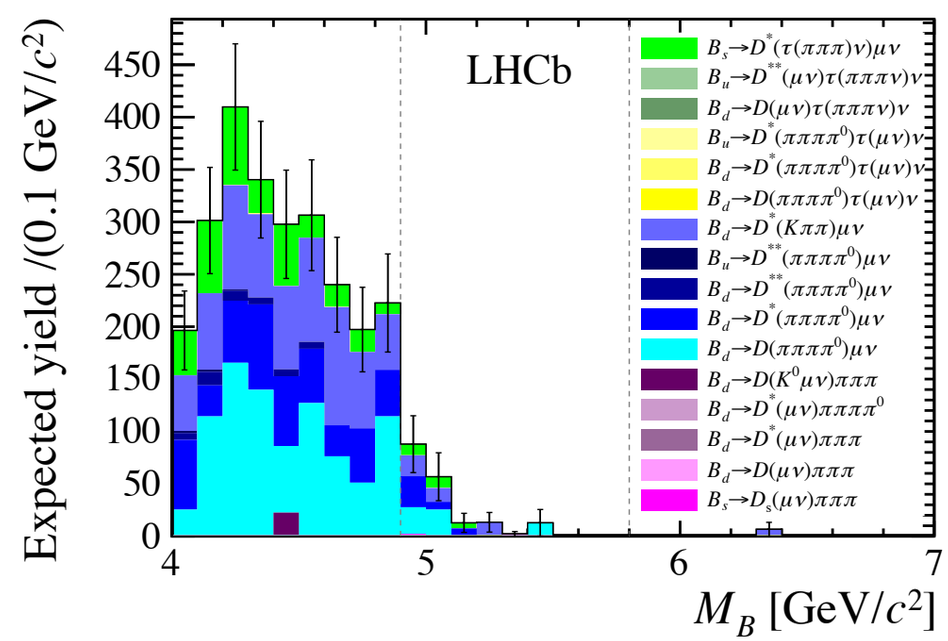
$B_{d,s} \to \tau\,\mu$ / additional material

[ArXiv:1905.06614]

After preselection



After full selection



The a_1 and ρ mediating the $\tau \to 3\pi\nu$ decay are exploited for background removal: