Lepton Flavor and Baryonic Flavor Violating Searches at LHCb

Rosa Anna Fini
(INFN – Bari, Italy)
on behalf of the LHCb collaboration

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The LHCb experiment

Precision studies of b and c-hadron decays: test SM/evidence NP

Requirement: Low background + High yields

good mass resolution & particle identification — efficient trigger and selection

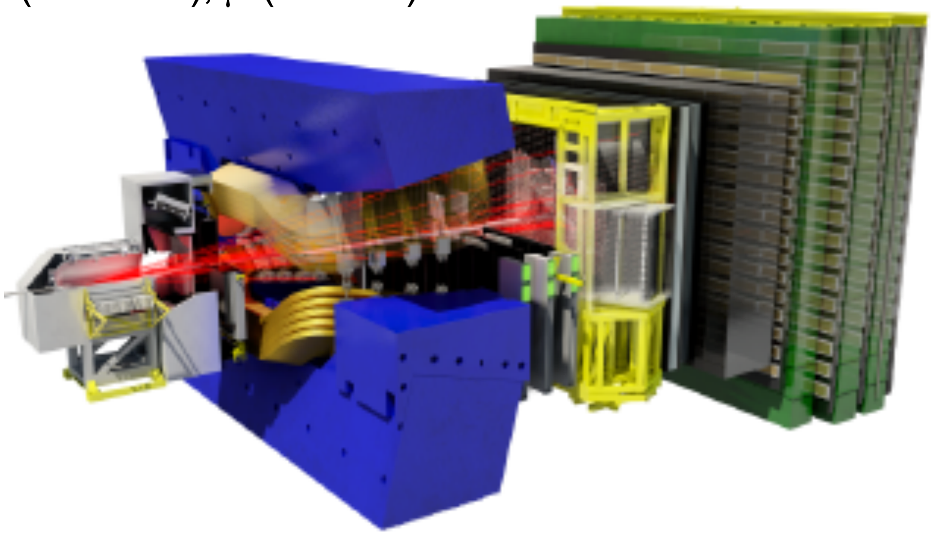
Vertexing & Tracking: σ_p/p~0.4%-0.6% (p from 5 GeV/*c* to 100 GeV/*c*), $\sigma_{IP}<20\mu m$

Particle identification: π/K/p (RICH), π^0/e/γ (E/HCAL), μ (MUON)

Trigger L0 (hardware: high p_t *e*/γ/*h*/μ)

HLT1&HLT2 software, event reconstruction

~90% efficient for dimuon channels



pp collisions @ LHC

(levelled inst. lumi $\mathcal{L}$~$4x10^{32}cm^{-2}s^{-1}$)

Run 1 (2011-2012) : 3 fb^{-1} @ 7-8 TeV

Run 2 (2015-2018) : 6 fb^{-1} @ 13 TeV

σ_{cc}~2.4 mb [LHCb, JHEP 1603 (2016) 159]

σ_{bb}~110 μb [LHCb, PRL 118 (2017) 052002]

(13 TeV, LHCb acceptance)

[LHCb, JINST 3 (2008) S08005, Int. J. Mod. Phys. A30 (2015) 1530022]

Outline

- Lepton Flavor Violation

✓ $B_{d,s} \to e\mu$

✓ $B_{d,s} \to \tau\mu$

✓ $B^+ \to K^+ e\mu$

➢ Link to Lepton Flavor Universality

- Baryonic Flavor Violation

Lepton Flavor Violation

- Observation of neutrino oscillations ⟶ first evidence for LFV in neutral leptons
- Renewed interest of LFV phenomena in the Heavy Flavour sector
- LFV in the charged sector negligible in SM

LFV HF decays may occur in the SM via neutrino oscillations but highly suppressed:

➢ they are ~10^{-54}, beyond experimental reach

- Some NP models foresee indirect enhancements to accessible levels
- Any observation of a charged LFV decay ⟶ evidence for BSM

$B_{d,s} \to e\mu$ at LHCb

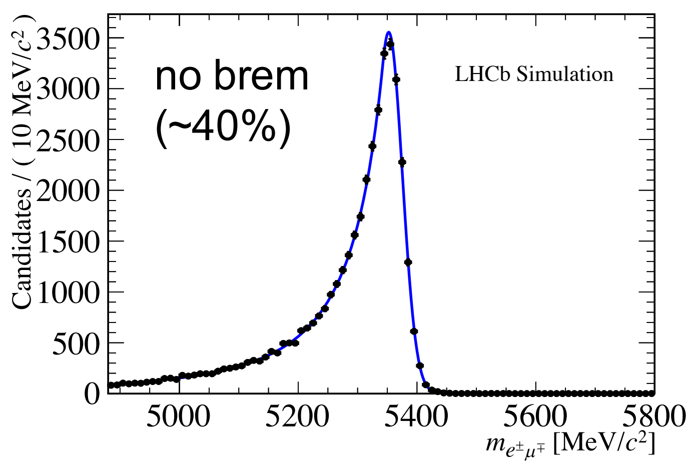
Search for: $B^0 \to e^\pm \mu^\mp$

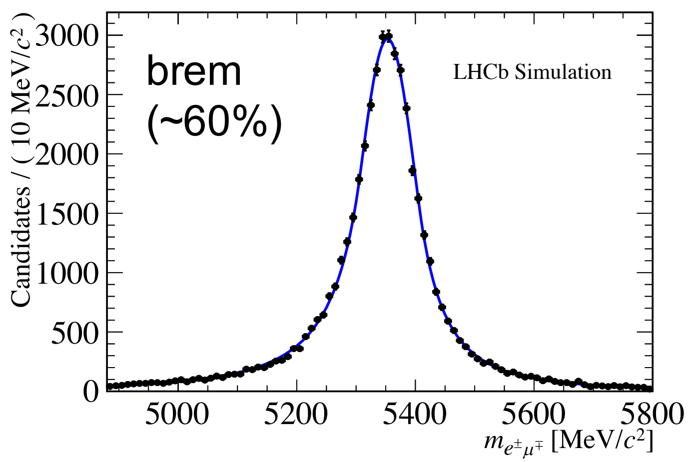
[LHCb, JHEP03 (2018) 078]

$B_s^0 \to e^\pm \mu^\mp$ all Run 1 data (3 fb^{-1})

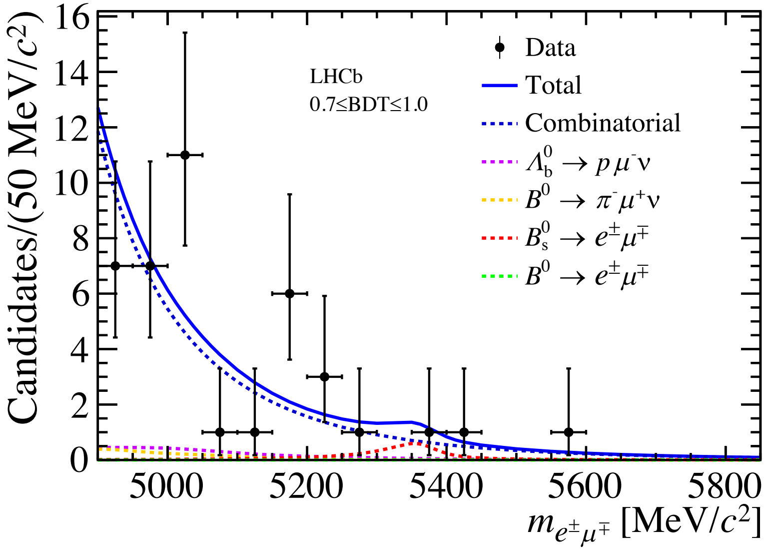
- Event selection: search for *e* and μ tracks forming a displaced vertex
- Efficiencies and mass shapes depend on whether or not the significant bremsstrahlung γ's from *e*'s are recovered

➢ 2 event categories analyzed separately





- Efficiencies from simulation; $\varepsilon_{trigger}$ and ε_{PID} from data calibration samples



- Combinatorial background: topological BDT, trained on signal MC vs same-sign data, calibrated on $B^0 \to K\pi$ data (proxy for the signal)
- Simultaneous invariant-mass fit to the two bremsstrahlung categories in BDT bins
- proton/pion mis-ID included
- ($B \to hh$, double mis-ID, not included)

Signal events normalised by means of two known channels:
$B^0 \to K^+\pi^-$ (same topology as the signal)
$B^+ \to J/\psi\, K^+$ (clean final state)

No excess in the signal region
Set upper limit: 90% (95%) C.L.

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

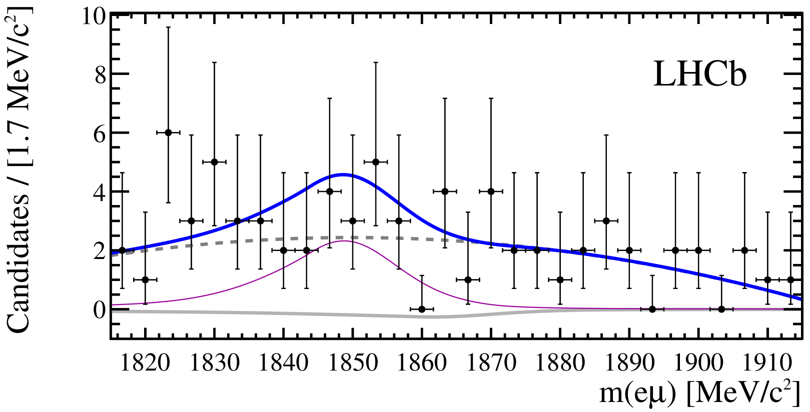
- ➢ previous best limit (1 fb^{-1}) superseded [LHCb, PRL 111 (2013) 141801]
- ➢ NP models: ~$O(10^{-11})$

$D^0 \rightarrow e\mu$ at LHCb

[LHCb, PLB 754 (2016) 167]

Search for: $D^0 \rightarrow e^{\pm}\mu^{\mp}$ all Run 1 data (3 fb^{-1})

- Candidates selected from $D^{*0} \rightarrow D^0\pi^+$
- Normalization channel: $D^0 \rightarrow K^-\pi^+$ (same topology as the signal)
- Main background from $D^0 \rightarrow \pi^+\pi^-$ (mis-ID π's, shown as purple line in the figure)
- Signal shapes from simulations



No significant excess over the expected background is observed; upper limits set at 90% C.L.

$$\mathcal{B}(D^0 \rightarrow e^{\pm}\mu^{\mp}) < 1.3 \times 10^{-8}$$

- Previous results improved by one order of magnitude [Belle, PRD 81 (2010) 091102]
- BMS models predictions range from $O(10^{-14})$ to $O(10^{-6})$

$B_{d,s} \to \tau\mu$ at LHCb

[LHCb, arXiv:1905.06614]

Search for: $B^0 \to \tau^{\pm}\mu^{\mp}$

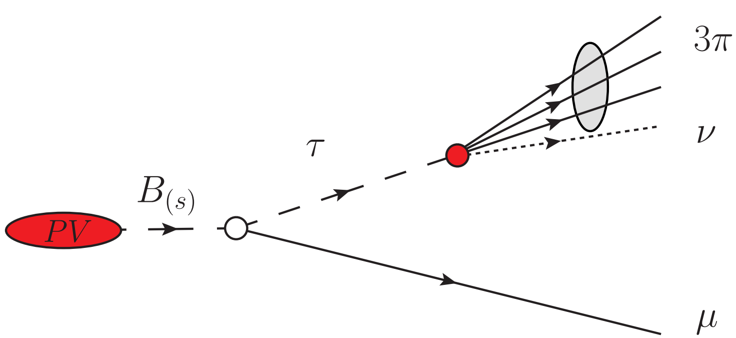
$B_s^0 \to \tau^{\pm}\mu^{\mp}$ all Run 1 data (3 fb^{-1})

Challenging search: at least one missing neutrino in the final state

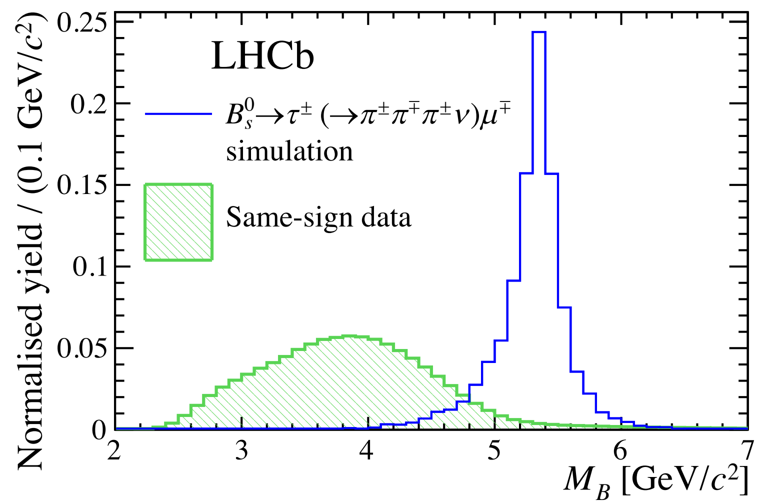
At LHCb focus on $\tau \to 3\pi\,\nu$ (~ 9.3% of τ decays) that allows to reconstruct the τ decay vertex

The μ combined with opposite charged τ to form a displaced vertex

Topological and kinematic constraints



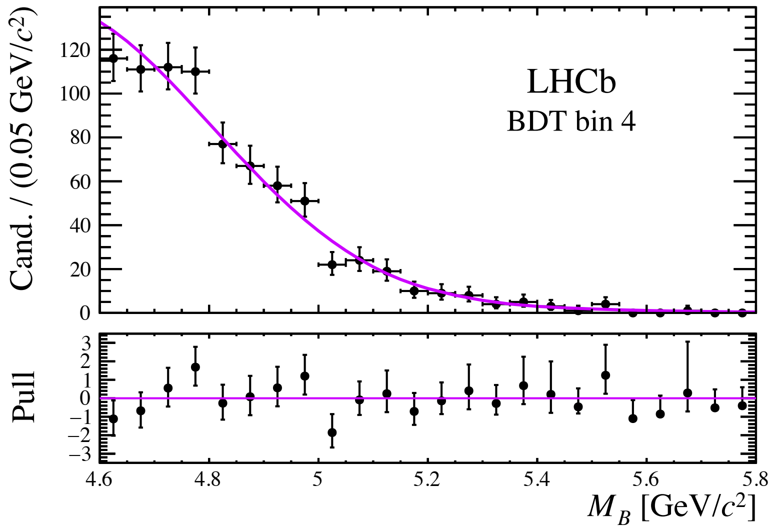
Same sign candidates and simulation to study the background



Retain candidates with M_B>4 GeV/c^2

[LHCb, arXiv:1905.06614]

- Isolation criteria and cut on τ decay time to reduce background
- BDT trained on signal MC vs upper mass sideband (>6.2 GeV) as background proxy



The search is performed in bins of BDT with increasing signal sensitivity

No presence of signal

$B^0 \to D(K\pi\pi)\pi$ as normalization channel

Upper limit at 95%CL

$$\mathcal{B}(B^0 \to \tau^\pm\mu^\mp) < 1.4 \times 10^{-5}$$
$$\mathcal{B}(B_s^0 \to \tau^\pm\mu^\mp) < 4.2 \times 10^{-5}$$

BaBar results improved by a factor 2(*)

First limit on this mode

(*) BaBar, PRD 77 (2008) 091104; BMS models predictions range from $O(10^{-9})$ to $O(10^{-5})$

$B^+ \rightarrow K^+ e\mu$ at LHCb

[LHCb, arXiv:1909.01010]

Search for: $B^+ \rightarrow K^+ \mu^- e^+$

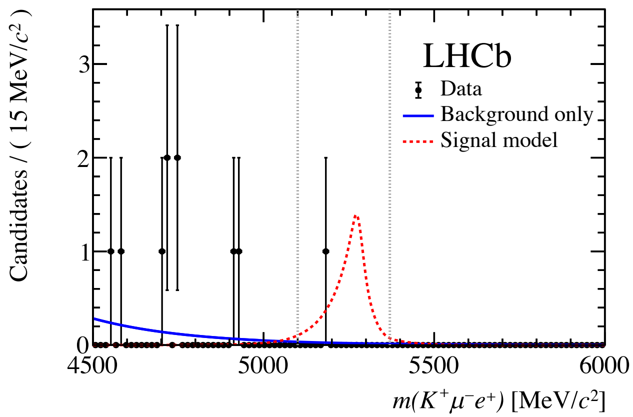
$B^+ \rightarrow K^+ \mu^+ e^-$ all Run 1 data (3 fb^{-1})

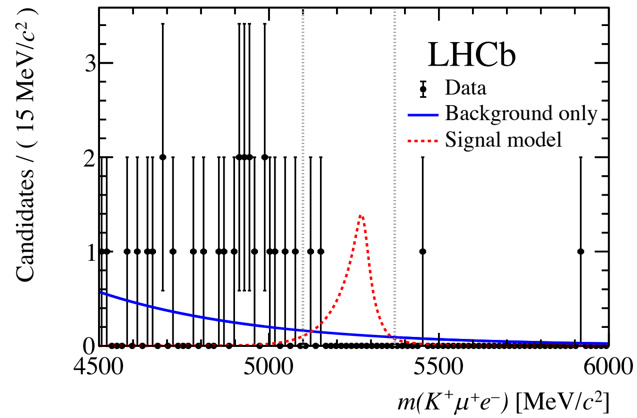
- The two final states are studied independently (maybe affected differently by BSM)
- Yields normalised to $B^+ \rightarrow K^+ J/\psi(\rightarrow \mu^+ \mu^-)$ (well known BF, same topology and detector signatures); $B^+ \rightarrow K^+ J/\psi(\rightarrow e^+ e^-)$ used as control channel.
- 3 charged tracks from a good-quality common vertex, displaced from PV
- Topological cuts, well identified particle (Cherenkov, Calorimetes, Muon Stations);
- Electron kinematics corrected for bremsstrahlung.
- Background: partially reconstructed B^+ decays (e.g. $B^+ \rightarrow D^0(\rightarrow K^+ Y l \nu) X l \nu)$
- mis-ID K and/or μ
- Combinatorial background: BDT algorithm, trained on simulated $B^+ \rightarrow K^+ e\mu$ upper-mass sideband used as a proxy
- Partially reconstructed *b*-hadron decays contribute to lower mass: a second BDT trained on lower-mass sideband in data.

- The performance of the PID algorithms is corrected using high purity samples from:
  - $B^{+} \rightarrow XJ/\psi(\rightarrow \mu^{+}\mu^{-})$ *for* μ
  - $B^{+} \rightarrow K^{+}J/\psi(\rightarrow e^{+}e^{-})$ for e
  - $D^{*+} \rightarrow D^{0}(\rightarrow K^{-}\pi^{+})\pi^{+}$ *for K*
- Dedicated simulated samples used to study potential contamination from *b*-hadron decays in the signal mass region
- Two categories:
  - fully reconstructed B decays (at least one particle mis-ID) ($B^{+} \rightarrow K^{+}l^{+}l^{-}$, $B^{+} \rightarrow K^{+}J/\psi(\rightarrow l^{+}l^{-})$) and fully hadronic decays ($B^{+} \rightarrow K^{+}l\pi^{+}\pi^{-}$)
  - partially reconstructed decays (one particle not reconstructed or more particle are mis-ID) such as: $B^{0} \rightarrow K^{*0}l^{+}l^{-}$, $\Lambda^{0}_{b} \rightarrow pK^{-}l^{+}l^{-}$, $\Lambda^{0}_{b} \rightarrow pK^{-}J/\psi(\rightarrow l^{+}l^{-})$, $B^{+} \rightarrow D^{0}(\rightarrow Kp, \rightarrow Kl\nu)l\nu$
- All contaminations are found to be negligible
- The efficiencies are calculated taking into account all selections and are determined from calibrated simulation samples

Invariant-mass distribution modeled differently depending on whether or not bremsstrahlung photons have been included in momentum calculation for the electrons

Two unbinned maximum likelihood fits assuming only exponential background or signal





No significant signal is observed; upper limits at 90 (95)% C.L.

$$\mathcal{B}(B^+ \to K^+\mu^-e^+) < 7.0\ (9.5) \times 10^{-9}$$
$$\mathcal{B}(B^+ \to K^+\mu^+e^-) < 6.4\ (8.8) \times 10^{-9}$$

BaBar results improved by more than one order of magnitude (*)

(*) PRD73 (2006) 092001; these BF are predicted to be $O(10^{-8})$ – $O(10^{-10})$ in leptoquark and extended gauge boson or models including CP violation in the neutrino sector

Link to Lepton Flavor Universality

- In light of recent flavour anomalies in semileptonic $b \to sl^+l^-$ many SM extensions have been proposed that link LUV to LFV
- Interesting correlations between observables in some leptoquarks models

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

[JHEP 1612 (2016) 027]

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

$$\frac{\mathcal{B}(B_s \to \mu^+ e^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)_{(SM)}} \sim 0.01 \left(\frac{(1-R_K)}{0.23}\right)^2$$

$$\frac{\mathcal{B}(B_s \to \tau^+(e^-, \mu^-))}{\mathcal{B}(B_s \to \mu^+\mu^-)_{(SM)}} \sim 4 \left(\frac{(1-R_K)}{0.23}\right)^2$$

New R_K at LHCb

[LHCb, PRL 122 (2019) 191801]

- New R_K measurement with about twice as many B's as previous one
- Re-optimized analysis of RUN 1 data (3 fb^{-1})
- Added 2015 and 2016 datasets from RUN 2 (2 fb^{-1})
- The *ee* channel is the challenge of this analysis for bremsstralhung corrections on the electron momentum
- To cancel most of the systematic effets R_K is measured as a double ratio

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu\mu)}{\mathcal{B}(B^+ \to K^+ee)} \Big/ \frac{\mathcal{B}(B^+ \to K^+J/\psi(\to \mu\mu))}{\mathcal{B}(B^+ \to K^+J/\psi(\to ee))}$$

$$r_{J/\psi} = \frac{\mathcal{B}(B^+ \to K^+J/\psi(\to \mu\mu))}{\mathcal{B}(B^+ \to K^+J/\psi(\to ee))} = 1.014 \pm 0.035$$

$$R_K = 0.846^{+0.060}_{-0.054}(stat)^{+0.014}_{-0.016}(syst)$$

- The new analysis on Run 1 data (new analysis and reconstruction) agrees with the old one within 1 σ
- Compatible with the SM expectation at 2.5 σ

Baryonic Flavor Violating Searches at LHCb

Search for: $\tau^- \to \bar{p}\mu^+\mu^-$

[LHCb, PLB 724 (2013) 36]

$\tau^- \to p\mu^-\mu^-$

7 TeV Run 1 data (1 fb^{-1})

Inclusive τ^- production cross section at LHCb ~80 μb (80% from $D_s \to \tau\nu$)

$\mu \longrightarrow$ clean signature in LHCb; *p* $\longrightarrow$ RICH excellent identification

Selection of a displaced vertex from the PV, having three tracks that are reconstructed to give a mass close to that of τ

Background: well identified μ and *p* are required

Topological and kinematic cuts (e.g. on p_T of reconstructed τ)

BDT used, trained using signal and background samples from simulation

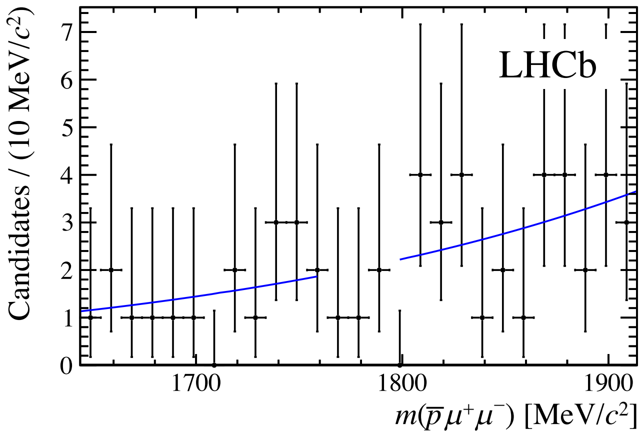
The channel $D_s^- \to \phi(\to\mu^+\mu^-)\pi^-$ used as calibration and to shape the invariant mass in the simulation

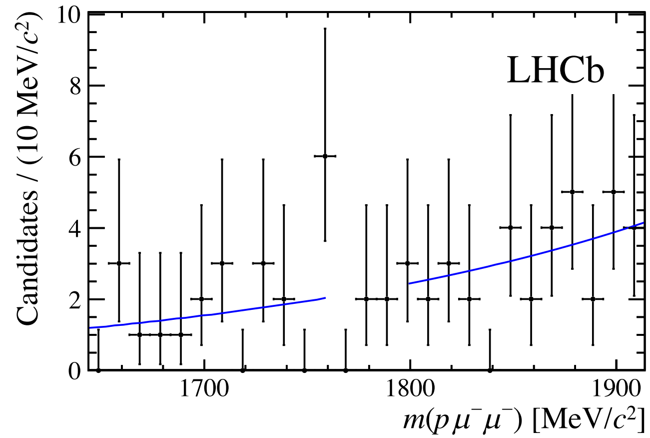
Reconstruction, selection and trigger efficiencies evaluated from simulation

[LHCb, PLB 724 (2013) 36]

PID efficiency is calculated using data calibration samples of $J/\psi \rightarrow \mu^+\mu^-$ and $\Lambda \rightarrow p\pi^-$

No peaking background expected (from simulation studies); background fitted with exponential line excluding signal window.





No evidence has been found for any signal; limits have been set at 90% (95%) C.L.

$$\mathcal{B}(\tau^- \rightarrow \bar{p}\mu^+\mu^-) < 3.3\ (4.3) \times 10^{-7}$$
$$\mathcal{B}(\tau^- \rightarrow p\mu^-\mu^-) < 4.4\ (5.7) \times 10^{-7}$$

First direct upper limits for two τ decay modes that violate both baryon number and lepton flavour

Conclusions and Outlook

- Any observation of Baryonic Number Violation or charged Lepton Flavour Violation would be a clear sign for BSM physics
- A lowering of the experimental upper limits on Branching Fractions will further constrain the parameter spaces of BSM models
- Hints of lepton non-universality in B decays demand searches for LFV decays

- All presented LHCb limits will be soon updated using the Run 2 dataset
- Many more LFV measurements being performed not only on B decays
- Some other baryon number violation analyses are ongoing (e.g. $B_s \rightarrow p\mu$)

- LHCb upgrade installation started this January 2019 to be ready in 2021, upgrade detector qualified to accumulate 50 fb^{-1} by the end of 2029
- LHCb collaboration is proposing a new major upgrade of the detector (CERN-LHCC-2018-027) for HL-LHC (increase data sample up to 300 fb^{-1})

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Thank you!

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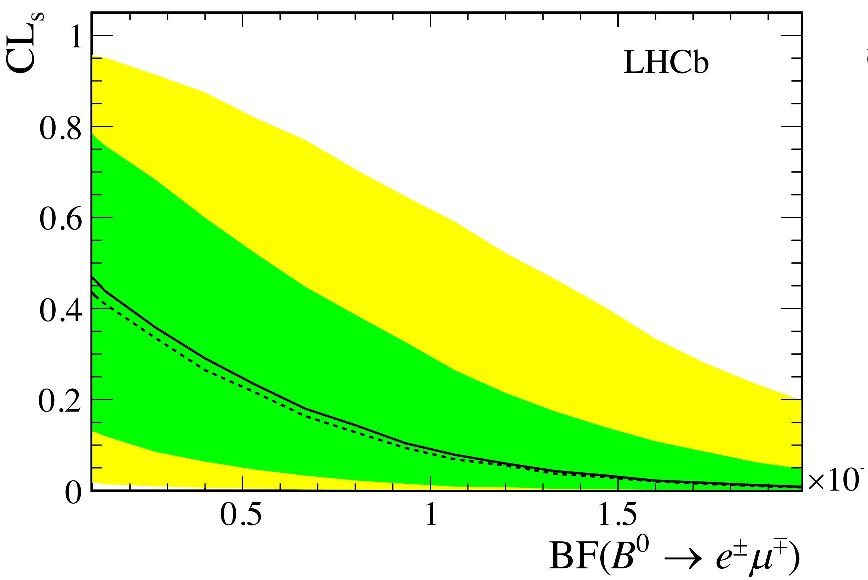
Spares

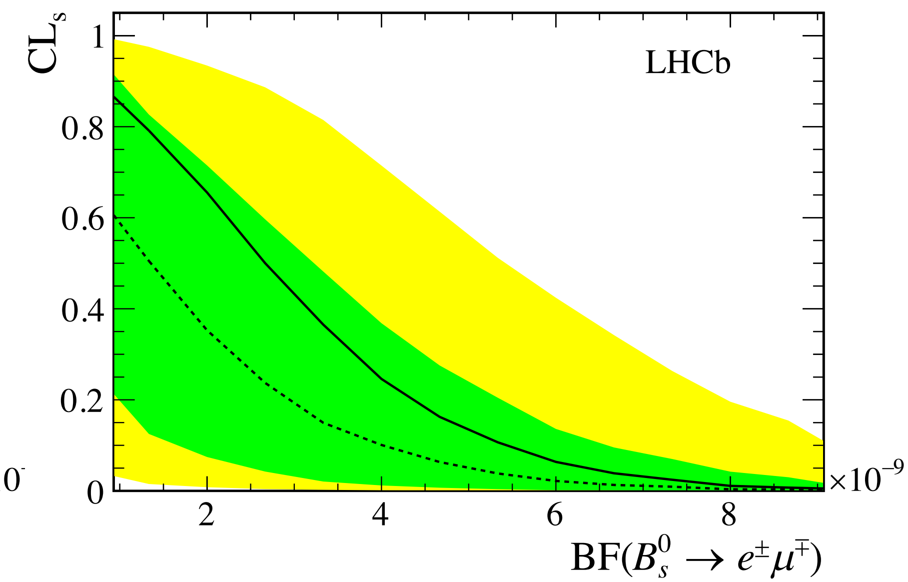
Other numbers for LHCb

- Focus on forward direction($2<\eta<5$): highly boosted b quark production at LHCb
- ➢ Cover 27% (25%) of (pair) production while instrumenting <3% of the solid angle
- ➢ Boosted CM energy helps to reconstruct vertices (B mesons fly ~ 1 cm)
- Trigger: ~90% efficient for dimuon channels, ~30% for all-hadronic
- Tracking: σ_p/p~0.4%-0.6% (p from 5 GeV/*c* to 100 GeV/*c*), $\sigma_{IP}<20\mu m$
- Vertexing: σ_τ~45 fs for $B_s \rightarrow J/\psi\phi$
- PID: 97% μID for 1-3% $\pi \rightarrow \mu$ misID
- Dipole magnet polarity periodically flipped to change the sign of many reconstruction asymmetries

$B_{d,s} \rightarrow e\mu$

Distribution of CL_s values as a function of the assumed BF





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

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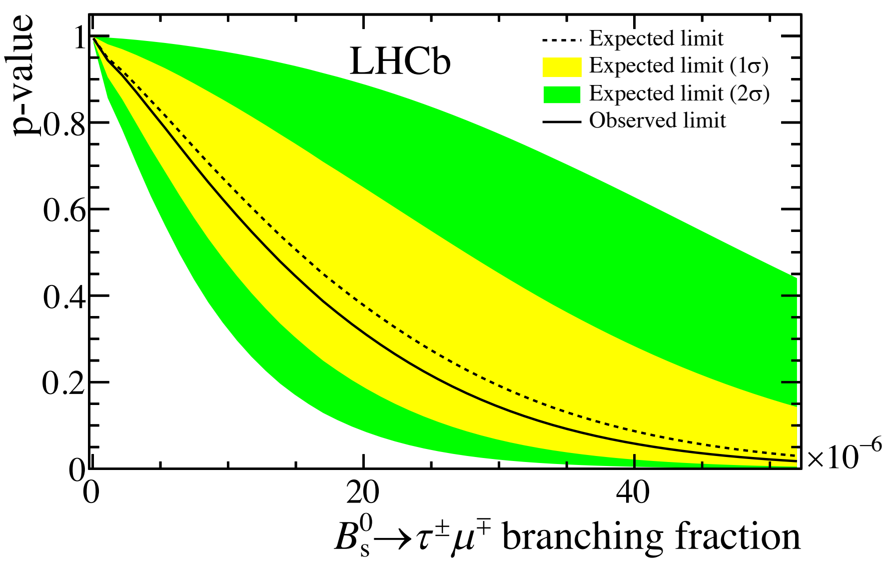
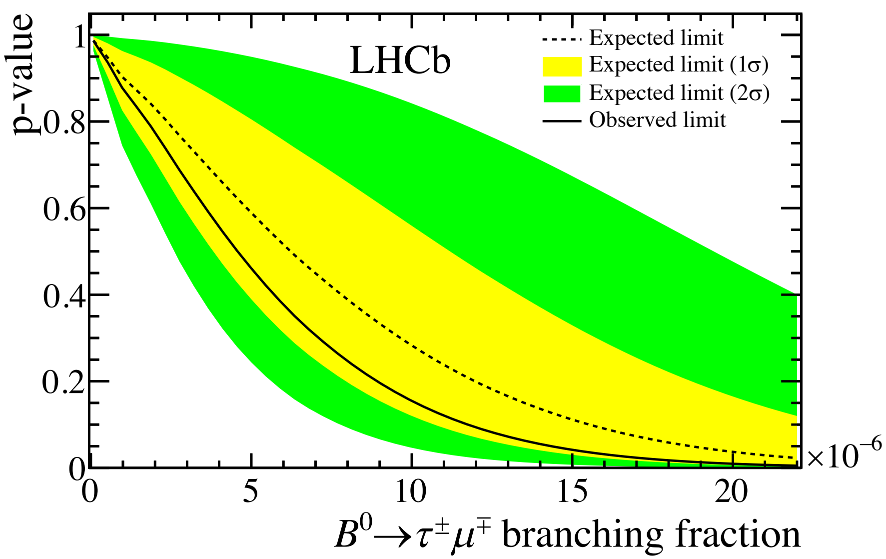
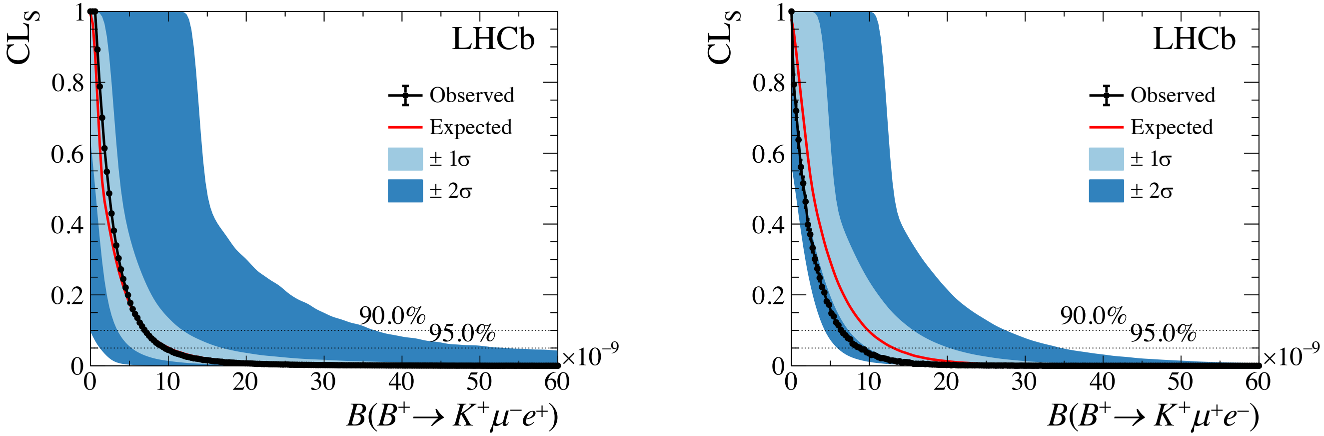




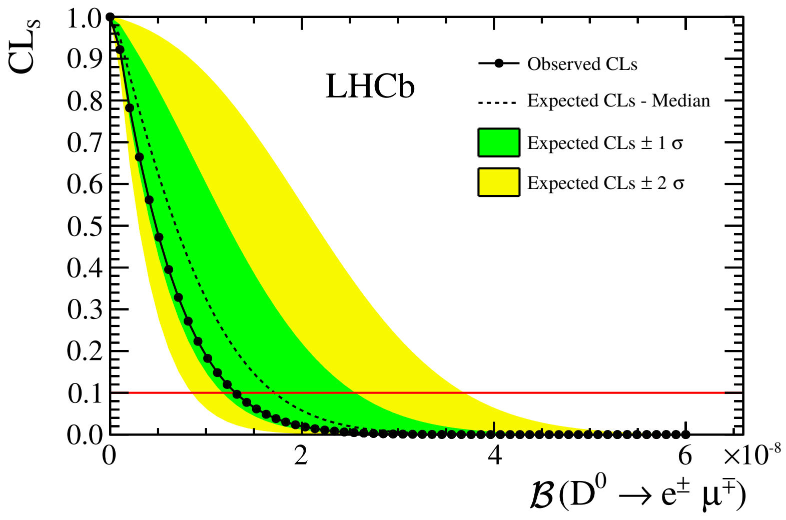
$B^+ \to K^+ e\mu$

Distribution of CL_s values as a function of the assumed BF



$D^0 \rightarrow e\mu$

Distribution of CL_s values as a function of the assumed BF



$\tau^- \rightarrow p\mu\mu$

Distribution of CL_s values as a function of the assumed BF under the hypothesis to observe background events only