Purely-leptonic rare decays at LHCb

ICHEP 2022

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9 July, 2022

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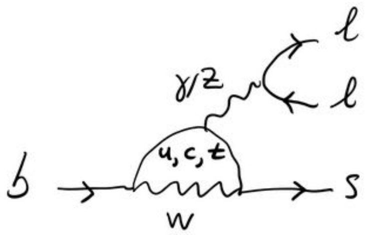
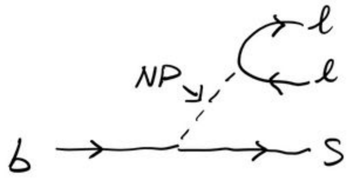
LHCb

Purely-leptonic rare decays

- **Rare decays are a powerful tool for searching for New Physics** (NP)
  - NP could have relatively high contribution compared to Standard Model contribution
- In the Standard Model, **Flavour-Changing-Neutral-Currents** (FCNCs) **forbidden at first order**
  - ***Hadrons decaying into two leptons*** combinations fall into this category

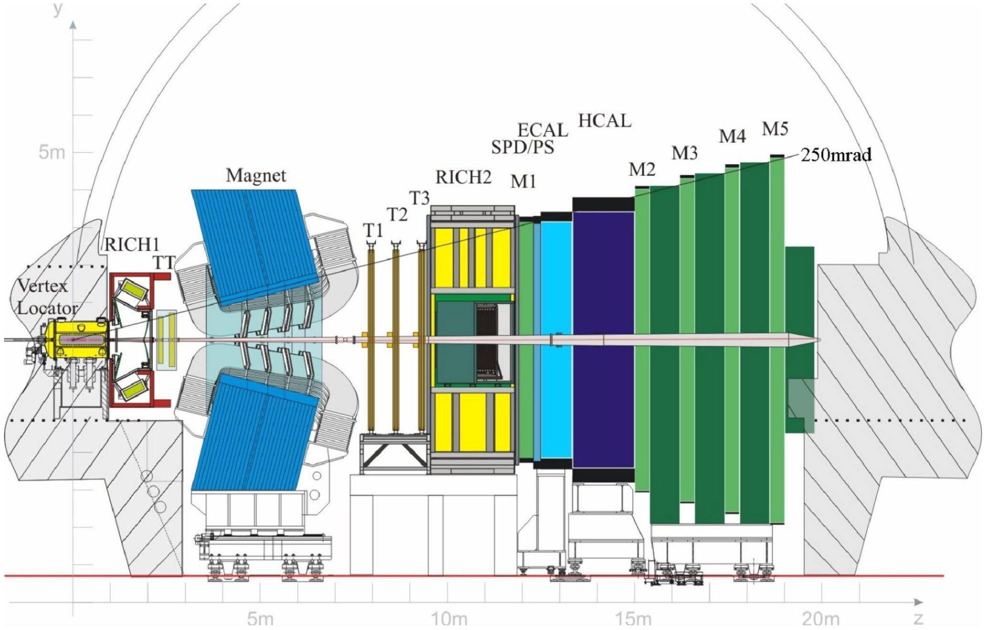




- **Hints at deviations** from SM **in *b→sll* transitions**
  - ***pure-leptonic provide additional constraints***
- ***Purely-leptonic decays*** **typically**
  - **Rarer in the SM** than FCNCs due to **helicity suppression**
  - **Theoretically cleaner** due to **no hadrons in final state**

JINST 3 (2008) S08005

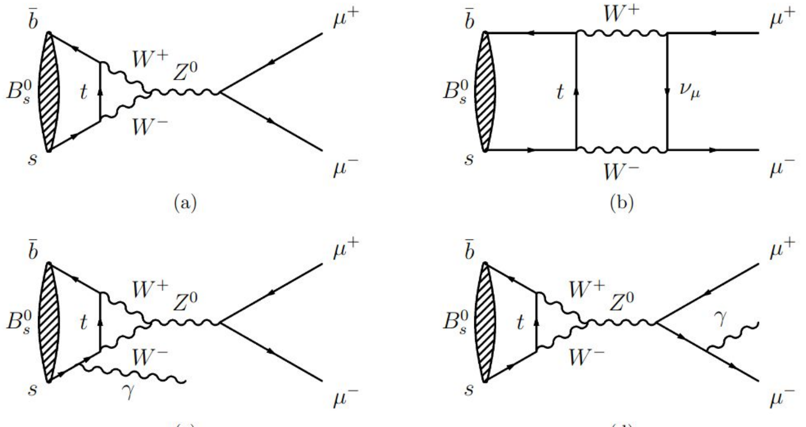
The LHCb experiment



- Forward spectrometer designed to study **heavy flavour physics**
  - Large production of heavy flavour at high energy pp collisions
- Good **vertexing** to search for **long-lived heavy flavour**
  - **Electron** (ECAL) and **muon ID** (M1-M5)
  - Charged hadron PID (RICH)
- Spectrometer setup offers good mass resolution
- 'Old' detector collected 9 fb^{-1} of *pp* collisions
- **New detector being commissioned right now!**

Phys.Rev.Lett. 128 (2022) 4, 041801
Phys.Rev.D 105 (2022) 1, 012010

B to two muons



- **Experimentally clean and efficient**
  - More on this next

- Most recent analysis includes **full Run 1 and Run 2**
  - *Legacy analysis of 'old' detector*
  - Both modes, B^0 and B_s
- **Additional observables!**
  - ***Accompanying photon(s) in final state*** *fully considered*
  - *Mixing of neutral mesons*
    - (Mixing of) **two mass eigenstates**, two life times
    - This degree of freedom leading to an **effective lifetime**

$$\tau_{\mu^+\mu^-} \equiv \frac{\int_0^\infty t\,\Gamma(B_s(t)\to\mu^+\mu^-)\,\mathrm{d}t}{\int_0^\infty \Gamma(B_s(t)\to\mu^+\mu^-)\,\mathrm{d}t} = \frac{\tau_{B_s^0}}{1-y_s^2}\left[\frac{1+2A^{\mu\mu}_{\Delta\Gamma_s}y_s+y_s^2}{1+A^{\mu\mu}_{\Delta\Gamma_s}y_s}\right]$$

$$\mathcal{B}(B_s^0\to\mu^+\mu^-) = \left[\frac{1+A^{\mu\mu}_{\Delta\Gamma_s}y_s}{1-y_s^2}\right]\mathcal{B}(B_s^0\to\mu^+\mu^-)_{t=0}$$

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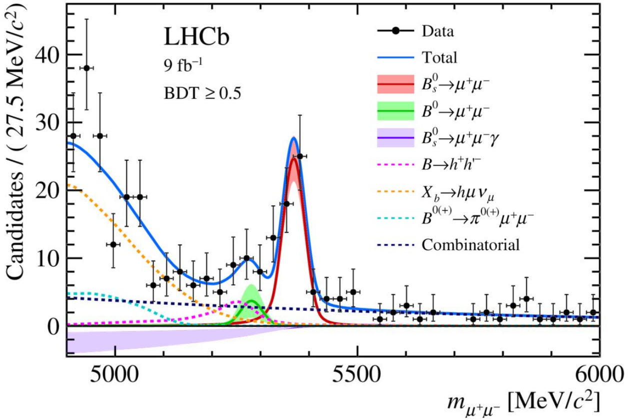
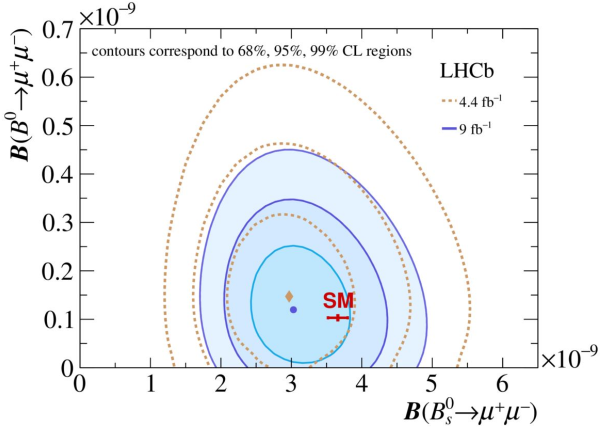
B to two muons *branching fractions*

- Good mass resolution leading to $\boldsymbol{B^0}$ and $\boldsymbol{B_s}$ **separation**
- Good ***vertexing and isolation*** with VELO sub-detector
  - High purity
  - Good decay time resolution, about 50 fs
- *Analysis and calibration*
  - **Multiple PID calibrations**
    - Hadronic mis-ID, especially important for B^0
  - **Classifier** (BDT) **calibration**
    - Using B to charged kaon / pion combinations
  - **Mass resolution** calibrated on multiple control channels





- $B_s^0 \to \mu^+\mu^-$ decays **observed** at 10 sigma C.L.
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 3.09^{+0.46+0.15}_{-0.43-0.11} \times 10^{-9}$
- $B^0 \to \mu^+\mu^-$ decays **not significant**, limit on branching fraction
  - $\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$ at 90% C.L.

[Phys.Rev.Lett. 128 (2022) 4, 041801](#)
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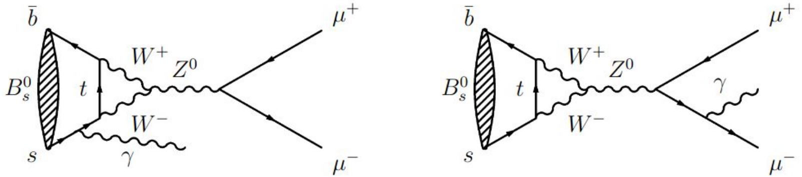
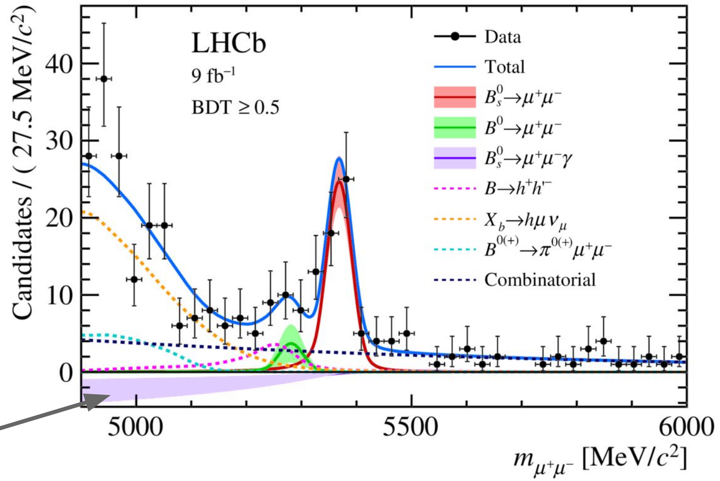
B to two muons *and a photon*

- Both **Initial State Radiation** (ISR) and **Final State Radiation** (FSR) considered *(respectively in plot)*



- **FSR** part of nominal analysis
  - **Soft photons** as a ‘radiative tail in invariant mass’
  - Default part of simulation [PHOTOS]
- **ISR** has **hard photons** and is experimentally distinguishable
  - Photon lifts helicity suppression
  - Now included in mass fit, **separate limit** set
- Observable limited by lower mass range
- Limit set at 90% C.L.

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)^{m(\mu\mu)>4.9\mathrm{GeV}/c^2} < 2.0 \times 10^{-9}$$



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B to two muons *effective lifetime*

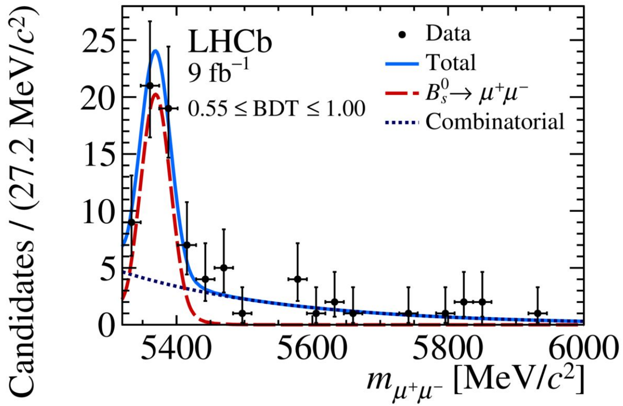
- **Effective lifetime sensitive to NP**

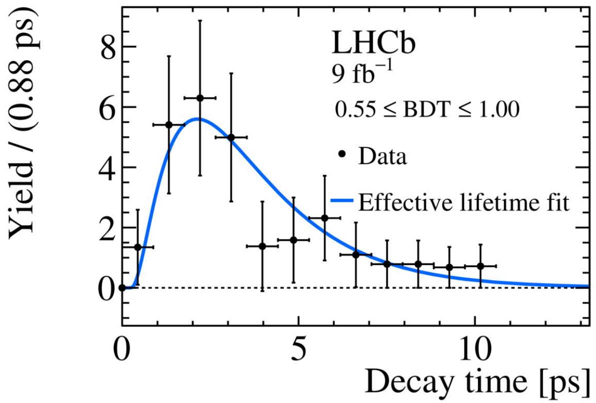
Strategy

- Only look at ***B_s mode***
- Fit in reduced mass window to remove mis-ID
- **Calibrate efficiency dependence on decay time**
  - Displacement requirement sculpting this efficiency
- **Background-subtraction with weights** *from invariant mass fit*
  - *sPlot* technique

$$\tau_{\mu\mu} = 2.07 \pm 0.29 \pm 0.03 \text{ ps}$$

Consistent with $A^{\mu\mu}_{\Delta\Gamma_s} = 1$ at 1.5σ





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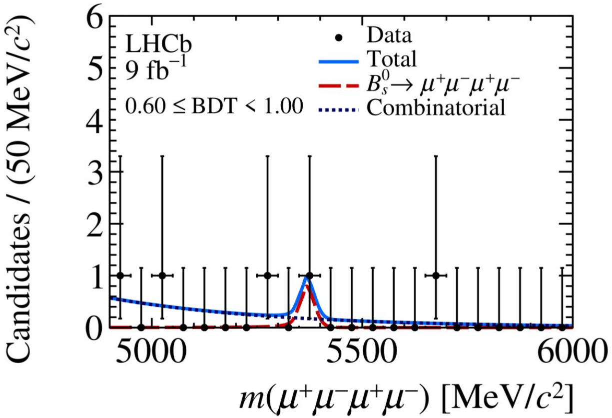
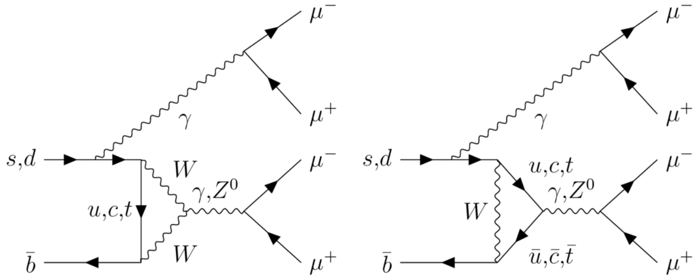
B to four muons



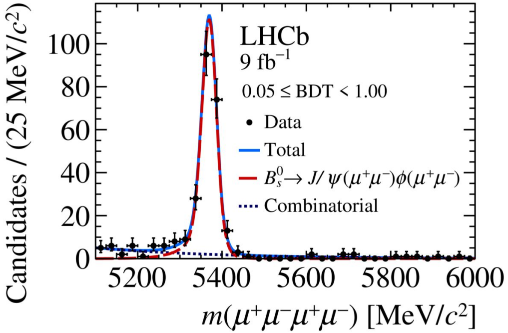
Limits at 95% C.L.

$$\mathcal{B}\left(B_s^0 \to \mu^+\mu^-\mu^+\mu^-\right) < 8.6 \times 10^{-10},$$
$$\mathcal{B}\left(B^0 \to \mu^+\mu^-\mu^+\mu^-\right) < 1.8 \times 10^{-10},$$
$$\mathcal{B}\left(B_s^0 \to a\left(\mu^+\mu^-\right) a\left(\mu^+\mu^-\right)\right) < 5.8 \times 10^{-10},$$
$$\mathcal{B}\left(B^0 \to a\left(\mu^+\mu^-\right) a\left(\mu^+\mu^-\right)\right) < 2.3 \times 10^{-10},$$
$$\mathcal{B}\left(B_s^0 \to J/\psi\left(\mu^+\mu^-\right) \mu^+\mu^-\right) < 2.6 \times 10^{-9},$$
$$\mathcal{B}\left(B^0 \to J/\psi\left(\mu^+\mu^-\right) \mu^+\mu^-\right) < 1.0 \times 10^{-9}.$$

- **More suppressed** than B to two muons
  - But more possibilities, including intermediate dimuon resonances
  - **Sensitive to different models**



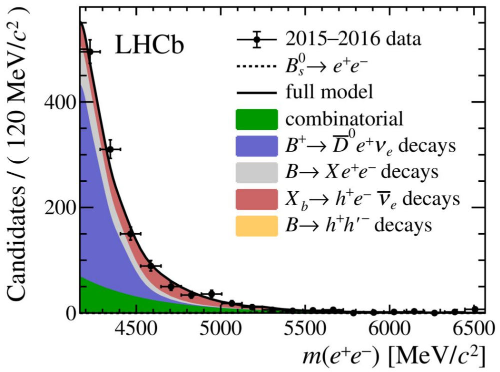
- ***Experimentally clean, normalisation mode with same final state***
  - J/Ψ and φ resonances

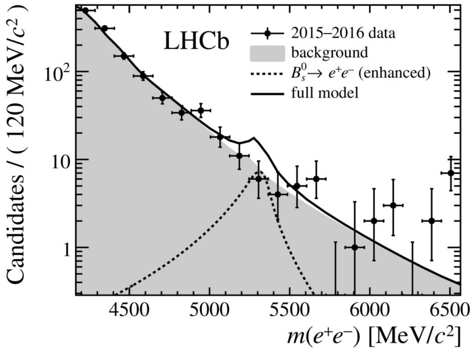


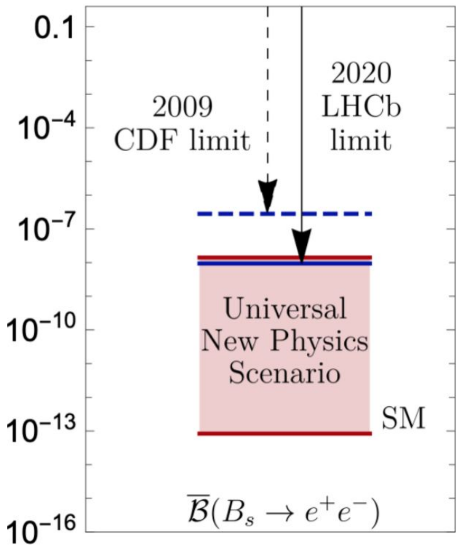
Phys. Rev. Lett. 124 (2020) 211802

B to two electrons

- Due to helicity suppression, SM prediction lower than B to two muons
- ***NP contributions up to 10^{-8}***, e.g. with no helicity suppression
- Analysis with Run 1 + Run 2 (up to 2016) data
- *Analysis with **electrons** harder due to **bremsstrahlung** losses*
- **World's best limit, entering NP scenario region**







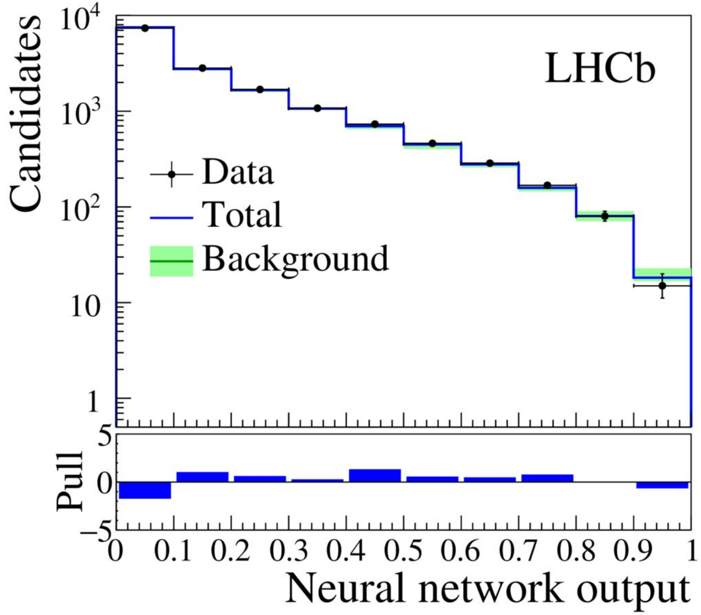
Limits at 90(95)% C.L.

$$\mathcal{B}(B_s^0 \to e^+e^-) < 9.4(11.2) \times 10^{-9} \qquad \mathcal{B}(B^0 \to e^+e^-) < 2.5(3.0) \times 10^{-9}$$

Phys. Rev. Lett. 118 (2017) 251802

B to two taus

- Search for B^0 and B_s to two taus
  - Much **less helicity suppressed** in SM
- Performed with Run 1 dataset, published in 2017
  - 3 fb^{-1}
  - Using **three pion** (visible) **final state** (of the tau)
- ***Fit to neural net output, invariant mass not fully reconstructable due to neutrinos***
- Normalized and calibrated to $B^0 \to D^- D_s^+$



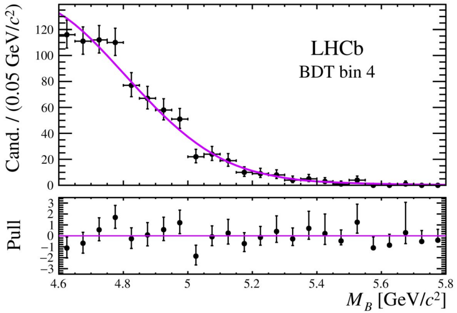
- No excess observed
- **First direct limit on Bs mode, world's best on the B mode**

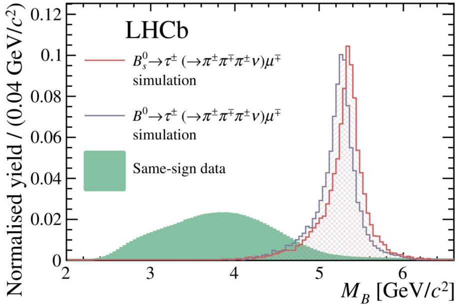
$\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ and $\mathcal{B}(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3}$ at 90% C.L.

B to electron muon / B to tau and muon

- *More forbidden than rare*
  - **Lepton Flavour Violation** (LFV) not in SM
  - Other talk on LFV at LHCb earlier today
- ***LFV present in many models explaining lepton non-universality***

- Both performed with **Run 1** dataset
- Both using classifier (similar to B to two muons)
- Both have to deal with **energy losses**
  - Neutrino or bremsstrahlung

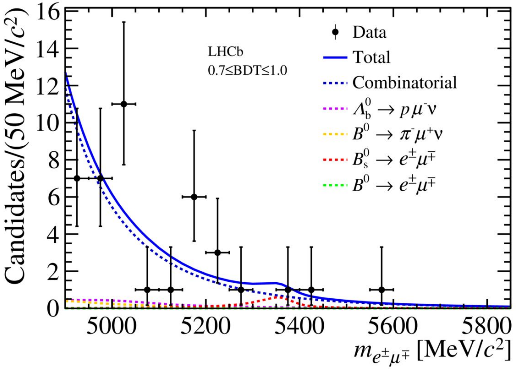




$$\mathcal{B}(B^0 \to \tau^\pm\mu^\mp) < 1.4 \times 10^{-5}$$
$$\mathcal{B}(B_s^0 \to \tau^\pm\mu^\mp) < 4.2 \times 10^{-5}$$
at 90% C.L.

Limits at at 90(95)% C.L.

channel	expected	observed
$\mathcal{B}(B_s^0 \to e^\pm\mu^\mp)$	$5.0\,(3.9) \times 10^{-9}$	$6.3\,(5.4) \times 10^{-9}$
$\mathcal{B}(B^0 \to e^\pm\mu^\mp)$	$1.2\,(0.9) \times 10^{-9}$	$1.3\,(1.0) \times 10^{-9}$



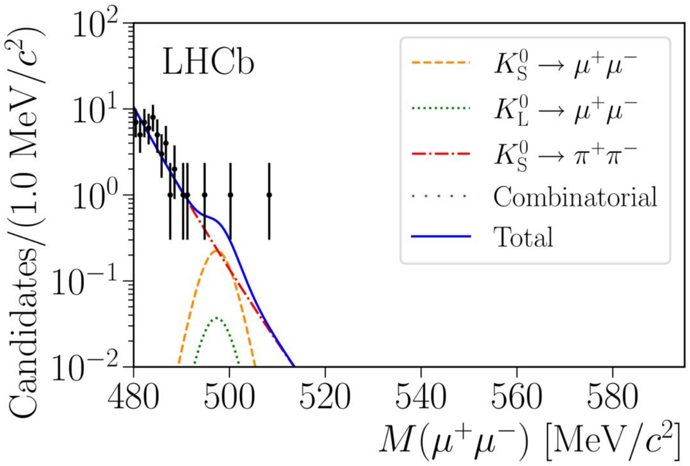
Phys. Rev. Lett. 125, (2020) 231801

Strange and Charm to leptons

- Similar interest as for B to two muons, but provides ***fuller picture with other quark flavours***
  - Typically lower branching fractions expected

- ***Rare charm decays in dedicated talk*** *last Thursday session*

- For example, **kaon to two muons**
  - Prediction for SM branching fraction on the order of $\mathbf{10^{-12}}$
  - Updated analysis with Run 2 data and *new trigger (on low pT muons)*



Limits - $\mathcal{B}(K^0_S \to \mu^+\mu^-) < 2.2\times10^{-10}$ reduced to $< 2.1\times10^{-10}$ at 90% confidence level when combined with Run1 result

Summary and prospects

- Purely-leptonic decays (of heavy flavour) **sensitive probes for New Physics**
  - ***Complementary information to B anomalies***
  - Many analyses performed and shown, including legacy (Run 1 and 2) B to two muons
- **Run 3 starting now**, with **5x higher luminosity** for LHCb!
- *Full software trigger*, including **higher efficiencies for leptons, especially electrons!**
- **Good prospects for fully leptonic decays!**