Rare B decays + Flavour anomalies at LHCb

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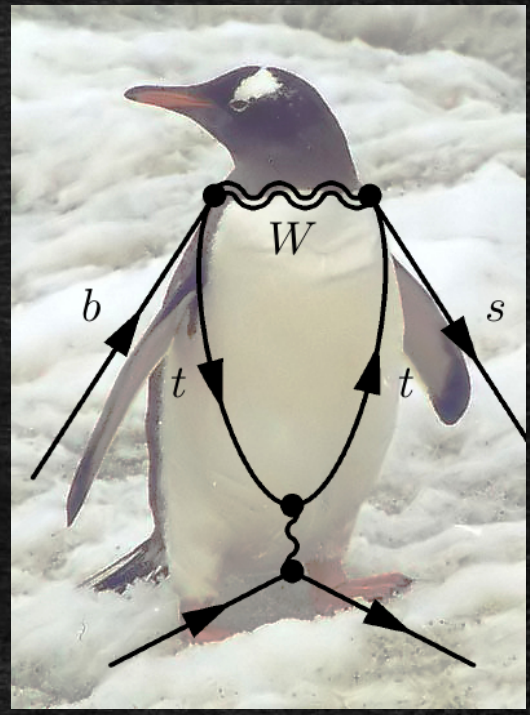
On behalf of the LHCb collaboration

IPA: Interplay between Particle and Astrophysics
TU Wien, 5-9 September 2022

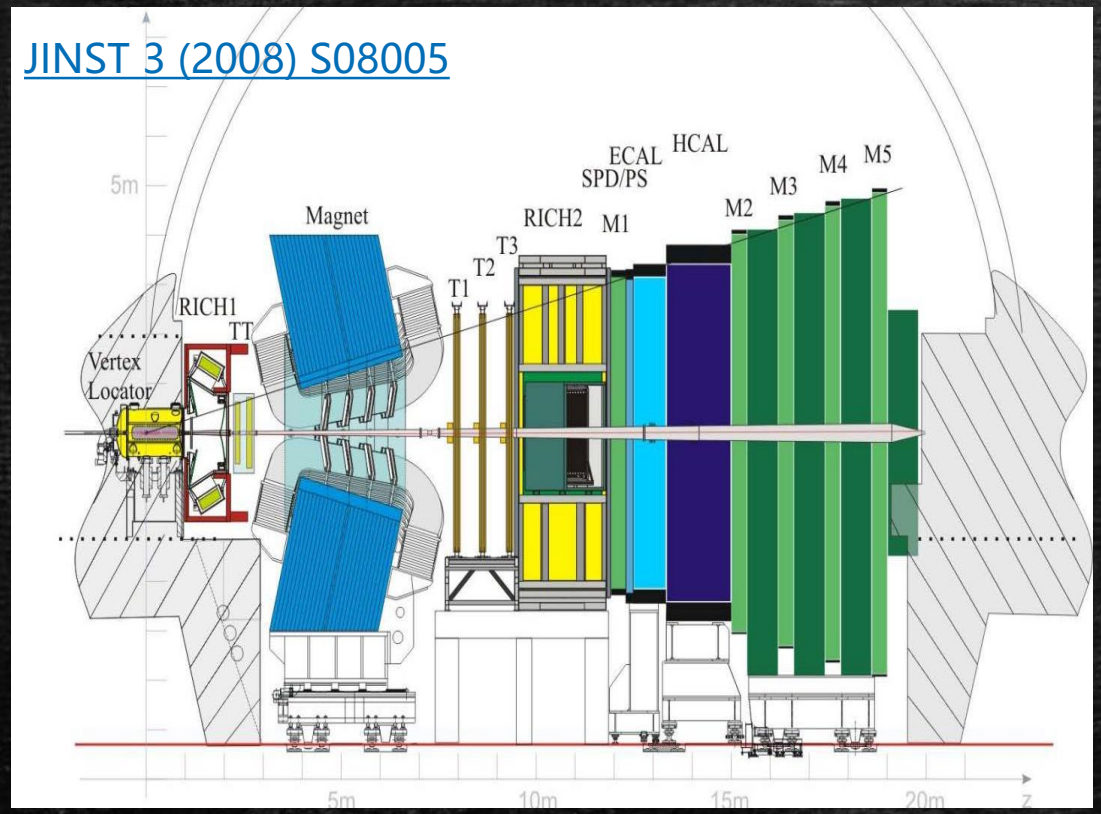
Physics

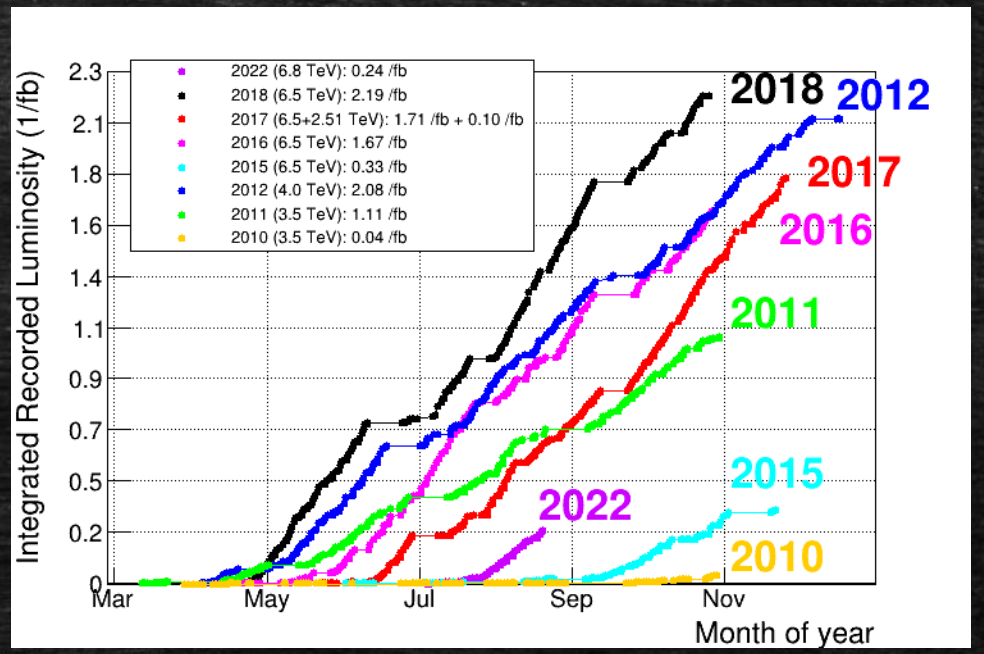
- **Why rare B decays?**
  - Strongly suppressed by the Standard Model (SM)
  - Sensitive to indirect effects of New Physics (NP)
  - Access to test couplings to 3rd generation quarks
- **Observables in experiments**
  - Branching fractions ("Br") and Angular observables
    - Searching for deviation from the SM predictions
    - Searching for violations in conservations
  - Lepton Flavour Universality (LFU) ratios ("RX")
    - Physics beyond the SM or Extensions to the SM



LHCb: A flavour physics detector with high luminosity

JINST 3 (2008) S08005





- Acceptance $2 < \eta < 5$
- Angle (mrad) $10 < \theta < 300$

- Forward spectrometer
- 9 fb^{-1} data (Run1 + Run2)
- Excellent tracking and PID performance

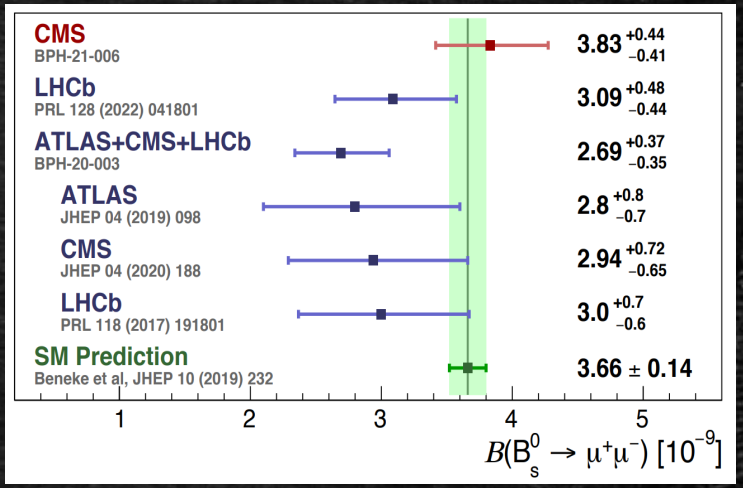
Searching for strongly suppressed / forbidden decays

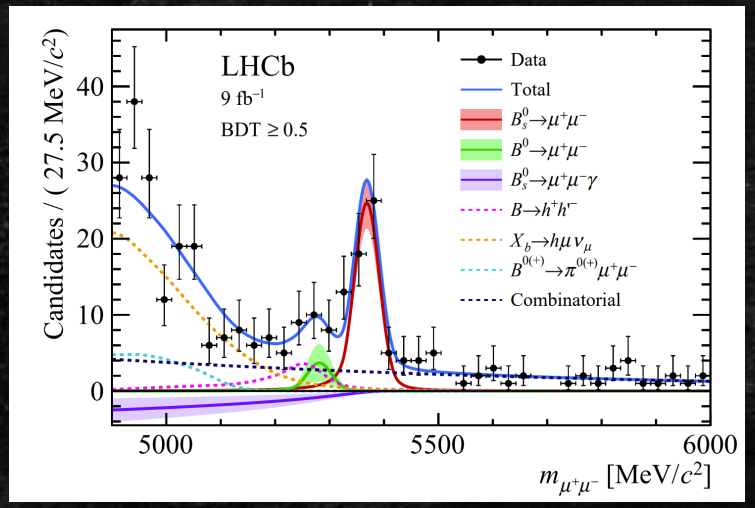
$B^0_{(s)} \to \mu^+\mu^-$

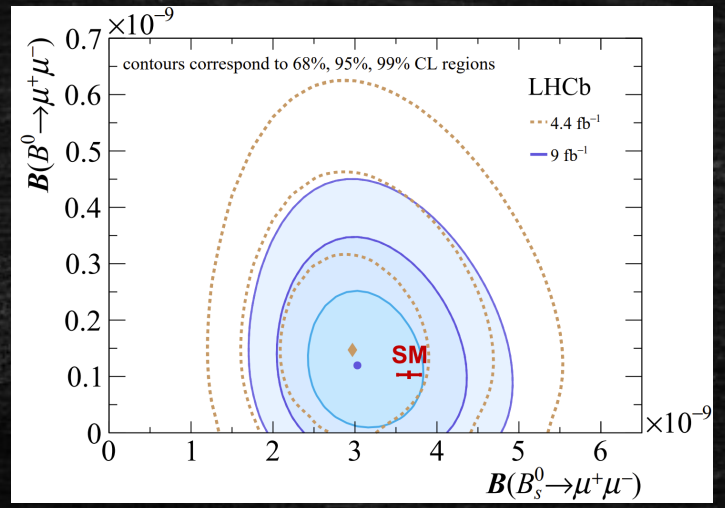
Run1 + Run2

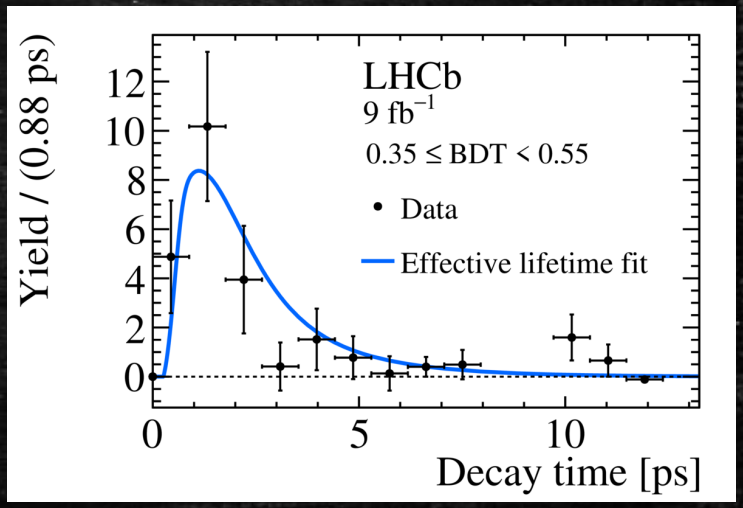
PhysRevLett.128.041801 & PhysRevD.105.012010

- Golden channel for searching new physics
  - Highly suppressed in SM: helicity suppressed + FCNC
  - Hadronic contributions are clear and well known from Lattice QCD
- **Results are consistent with SM predictions** within 2σ
  - $Br(B_s^0 \to \mu^+\mu^-) = 3.09^{+0.46\,+0.15}_{-0.43\,-0.11} \times 10^{-9}$, $Br(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$ @95% CL
  - $Br(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\,\mathrm{GeV}/c^2} < 2.0 \times 10^{-9}$ @95% CL
  - $\tau(B_s^0 \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03\ ps$



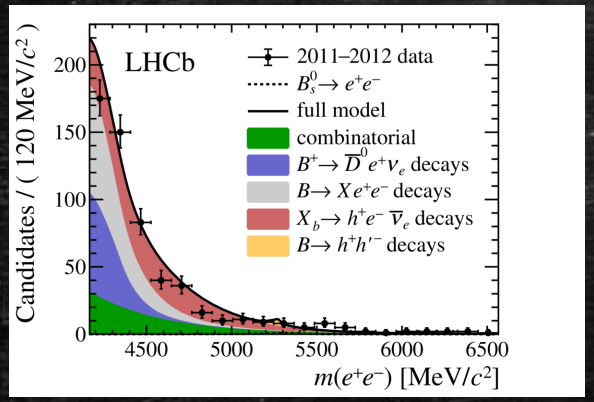


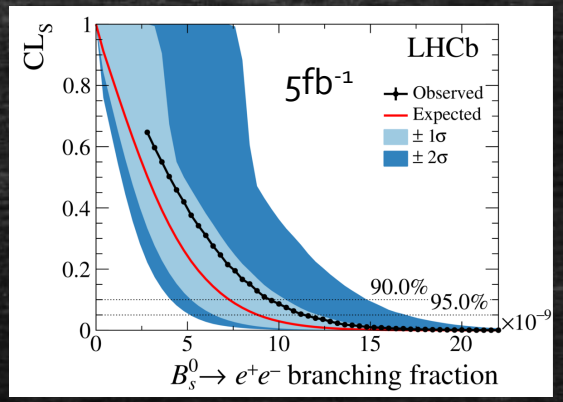


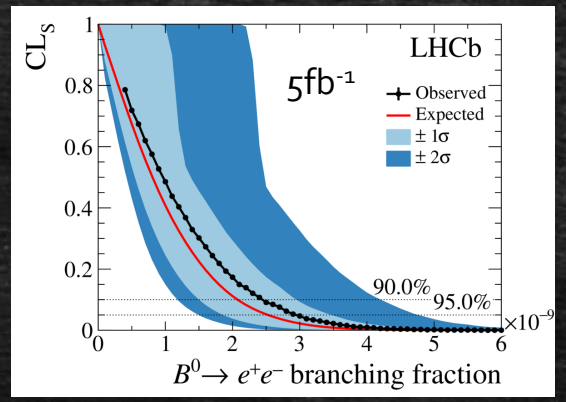


Other leptonic decays

- $B^0_{(s)} \to e^+e^-$ (PhysRevLett.124.211802), with Run1 and part of Run2 data







  - $Br(B^0_s \to e^+e^-) < 11.2 \times 10^{-9}$ @95% CL, $Br(B^0 \to e^+e^-) < 2.5 \times 10^{-9}$ @95% CL

- Also searched for $B^0_{(s)} \to \tau^+\tau^-$ (PhysRevLett.118.251802) with Run1 data (3 fb^{-1})
  - $Br(B^0_s \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ @95% CL, $Br(B^0 \to \tau^+\tau^-) < 2.1 \times 10^{-3}$ @95% CL

No signal event is observed

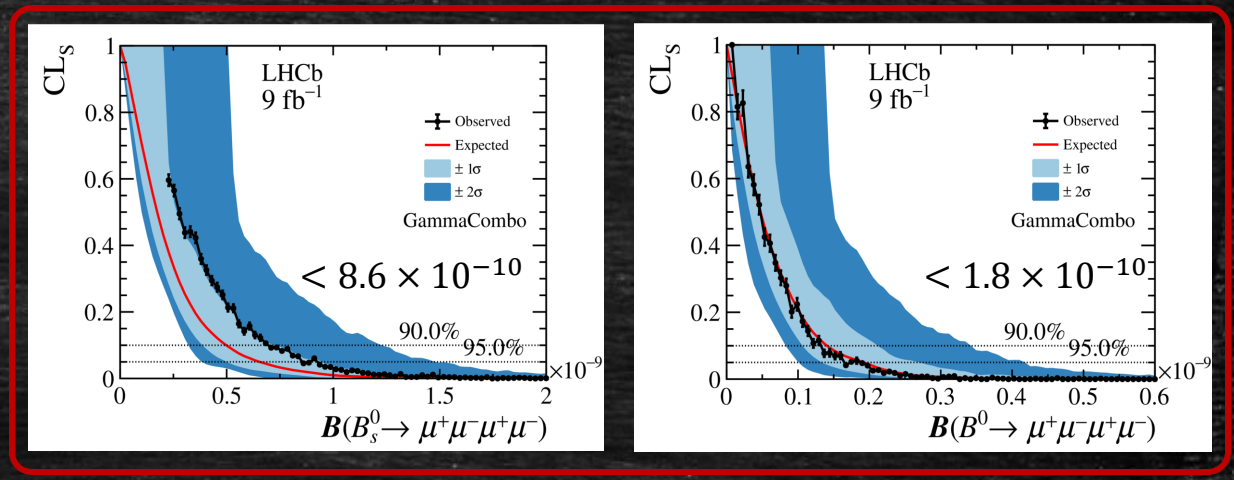
Br upper limits are consistent with SM predictions

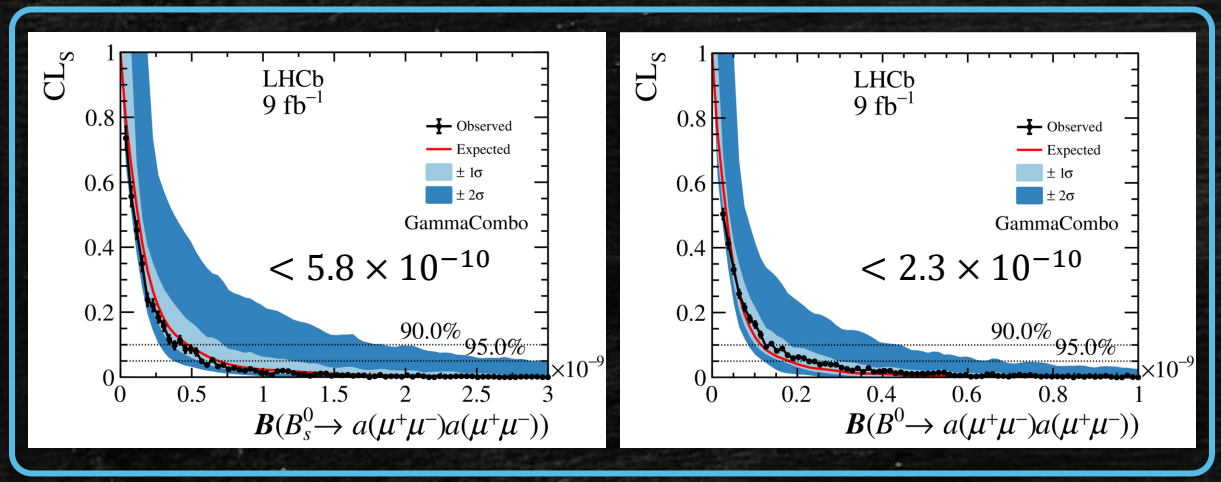
Analyses with full Run1 and Run2 dataset are ongoing

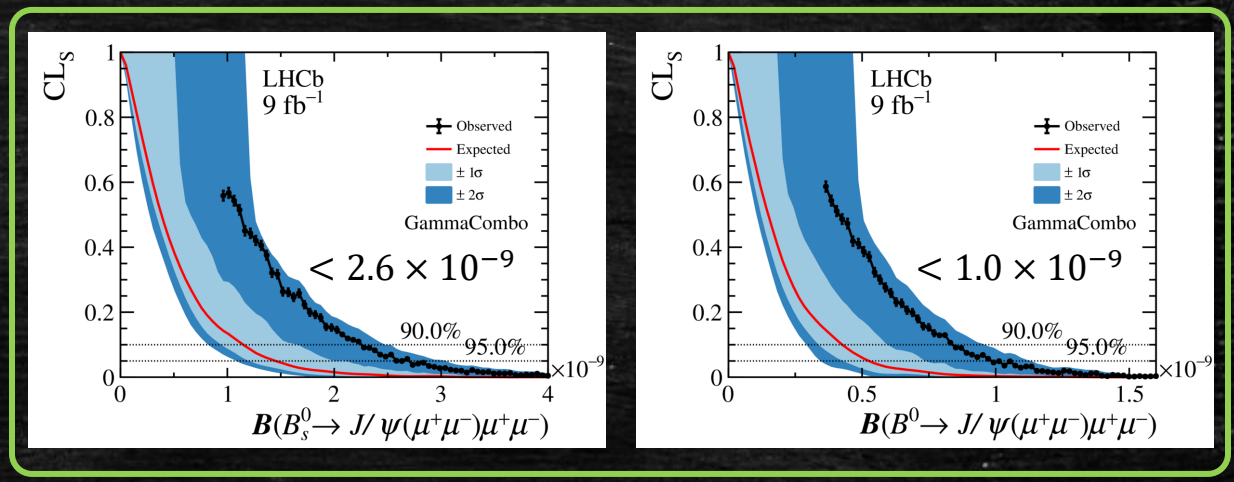
Other leptonic decays

Run1 + Run2

- $B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$ (JHEP03(2022)109)
  - Decays with resonances are also searched
    - $B^0_{(s)} \to a(\mu^+\mu^-)a(\mu^+\mu^-)$
    - $B^0_{(s)} \to J/\psi(\mu^+\mu^-)\mu^+\mu^-$
  - No signal is observed for all channels
  - Most stringent limits up to date @95% CL

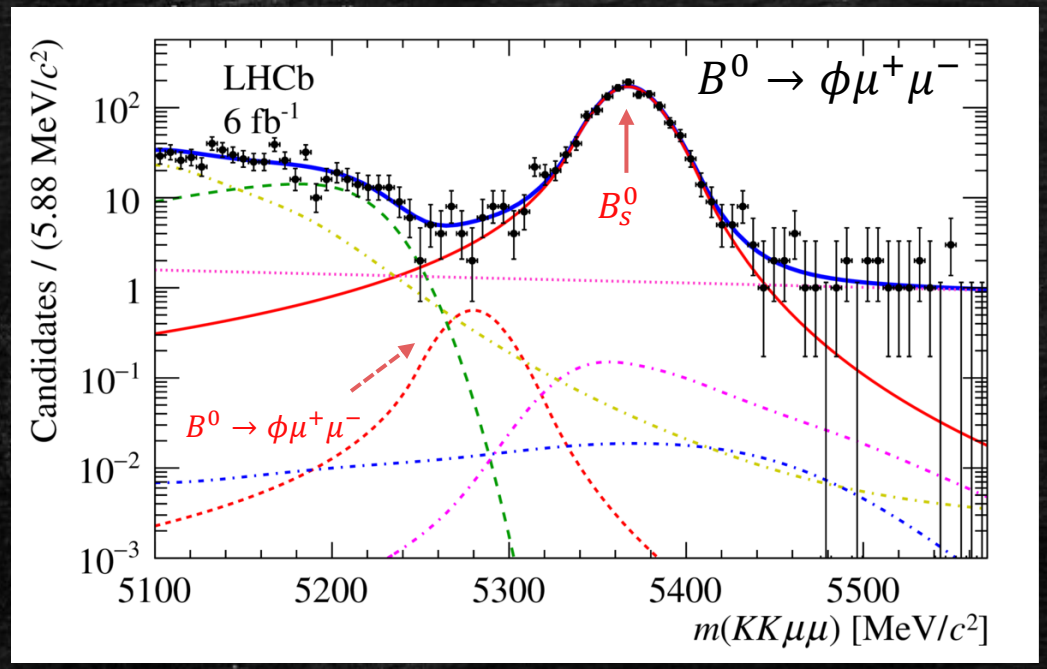


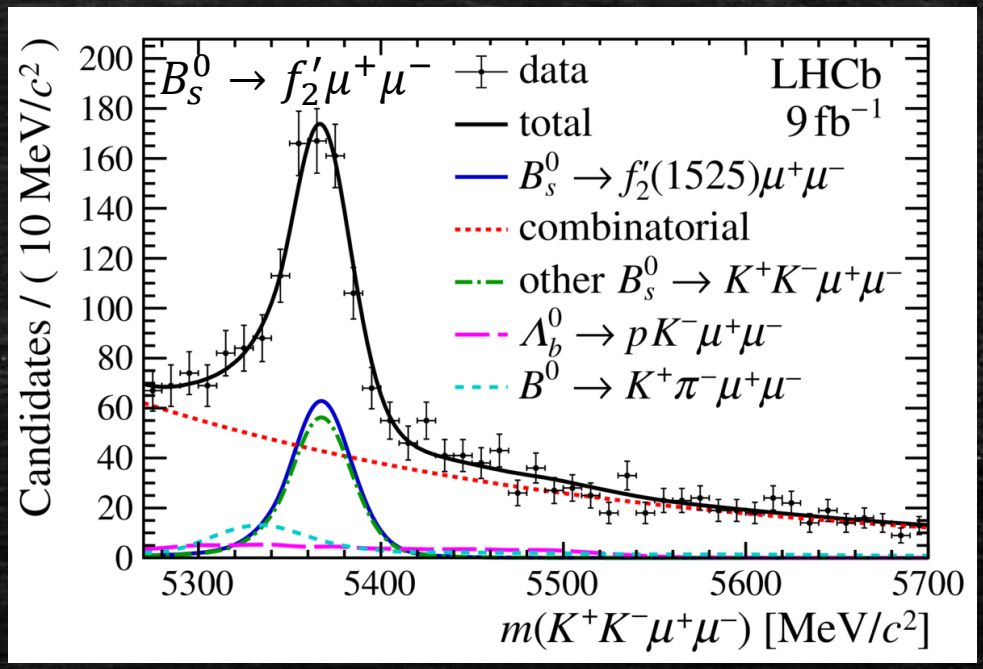




Other searching

- $B^0 \to \phi\mu^+\mu^-$ (JHEP05(2022)067)
  - Not observed, $Br(B^0 \to \phi\mu^+\mu^-) < 3.2 \times 10^{-9}$ @90% CL
- $B_s^0 \to f_2'(1525)\mu^+\mu^-$ (PhysRevLett.127.151801)
  - Observed at first time
  - $Br = \left(1.57 \pm 0.19_{stat.} \pm 0.06_{syst.} \pm 0.06_{q^2} \pm 0.08_{norm.}\right) \times 10^{-7}$





Lepton Flavour (Number) Violating (LFV/LNV) decays

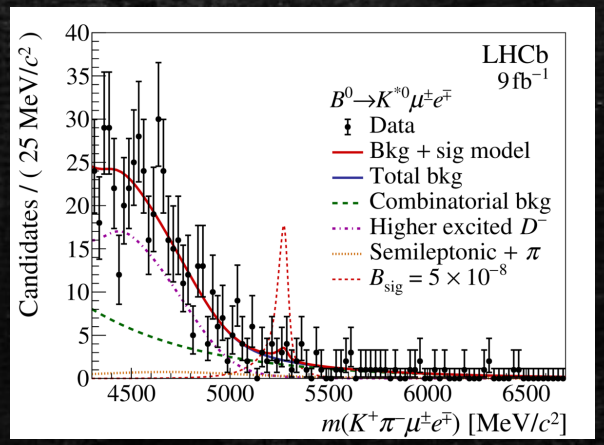
- LFV has been observed in neutrino sector ⇒ *May also exist in e/μ/τ?*
- An observation or a deviation will give clear sign for NP
  - *LNV ⇒ Matter-antimatter asymmetry?*

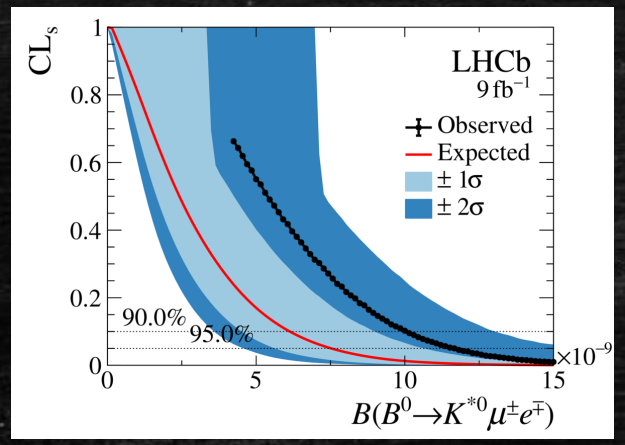
➢ $B_s^0 \to \phi\mu^\pm e^\mp$ & $B^0 \to K^{*0}\mu^\pm e^\mp$ (arXiv:2207.04005)

➢ No signal is observed in all 4 channels

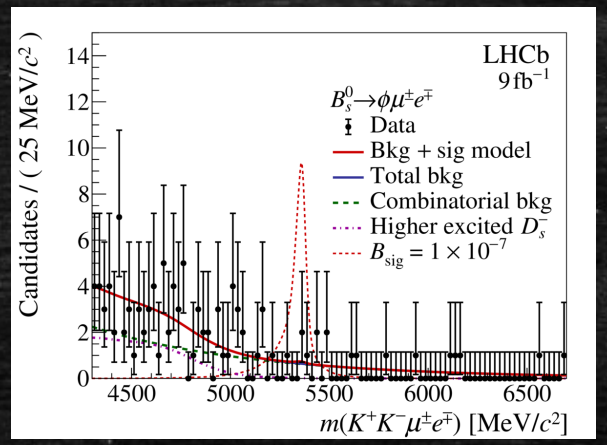
➢ $B_s^0 \to \phi\mu^\pm e^\mp$ is firstly searched and currently best upper limits are set

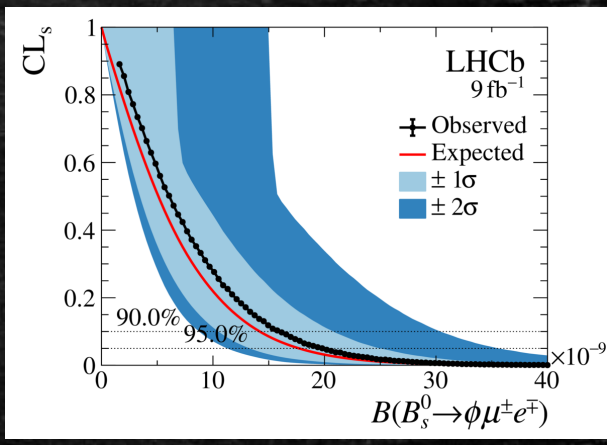
Run1 + Run2





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





$B_s^0 \to \phi\mu^\pm e^\mp$

Lepton Flavour (Number) Violating (LFV/LNV) decays

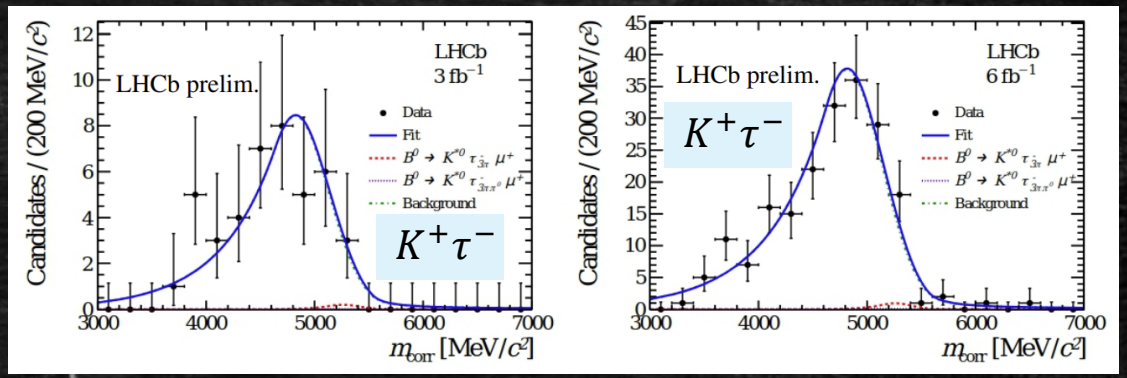
- $B^0 \to K^{*0}\tau^{\pm}\mu^{\mp}$ (LHCb-PAPER-2022-021, in prep.)

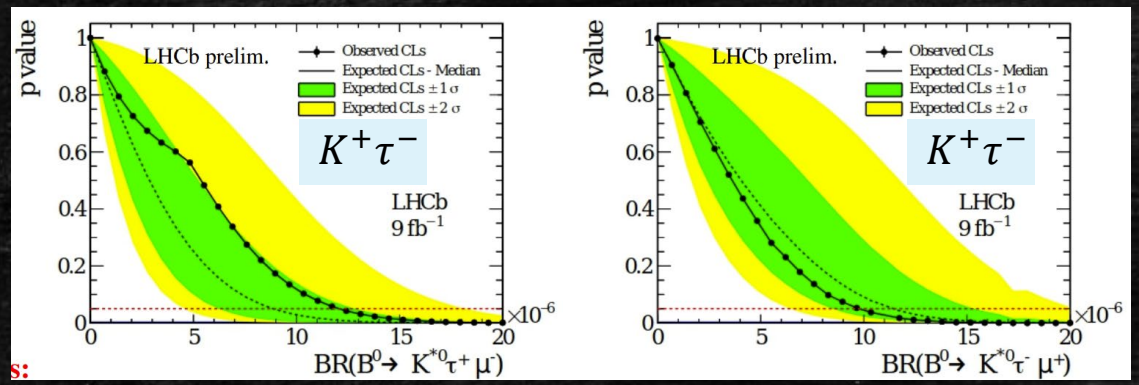
Run1 + Run2

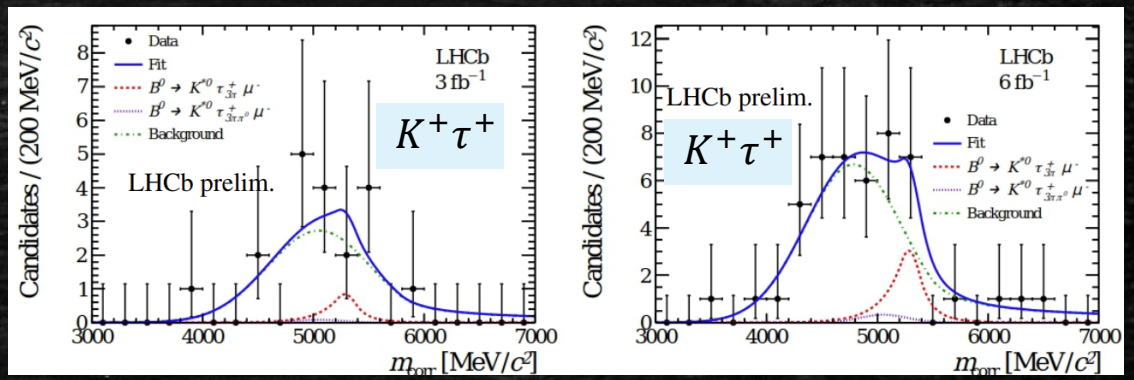
  - Partially reconstruct $\tau^{\mp}$: $\tau^{\mp} \to \pi^{\pm}\pi^{\mp}\pi^{\mp}(\pi^0)\nu_\tau$
  - Corrected mass: $m_{corr} = \sqrt{p_\perp^2 + m^2_{K^*\tau\mu}} + |p_\perp| \Rightarrow$ *Minimum mass of the reconstructed B*

- No signal is observed
  - $Br(B^0 \to K^{*0}\tau^+\mu^-) < 1.2 \times 10^{-5}$ @95% CL
  - $Br(B^0 \to K^{*0}\tau^-\mu^-) < 9.8 \times 10^{-6}$ @95% CL

First search on this decay mode!



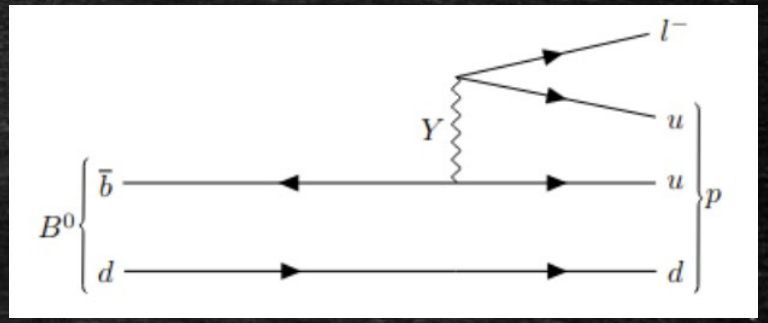




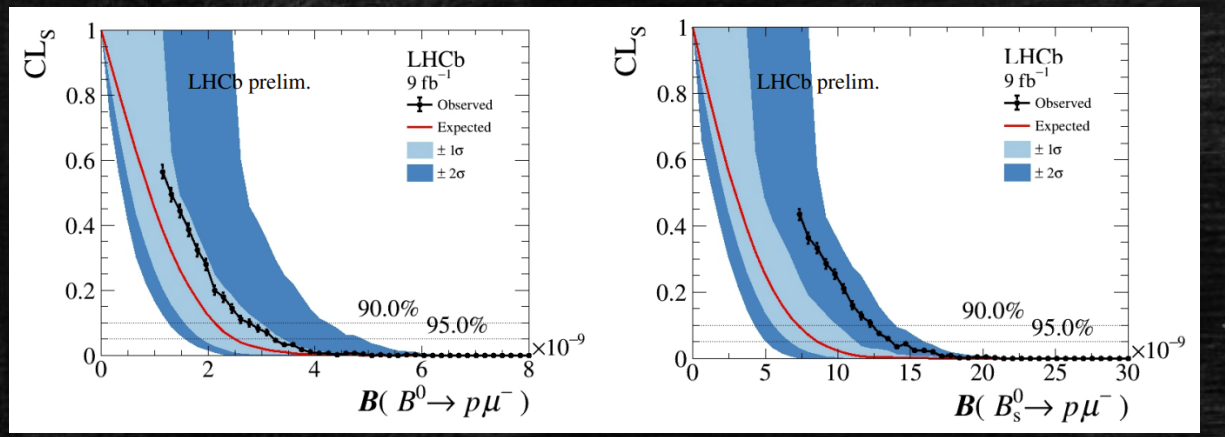
Lepton Flavour (Number) Violating (LFV/LNV) decays

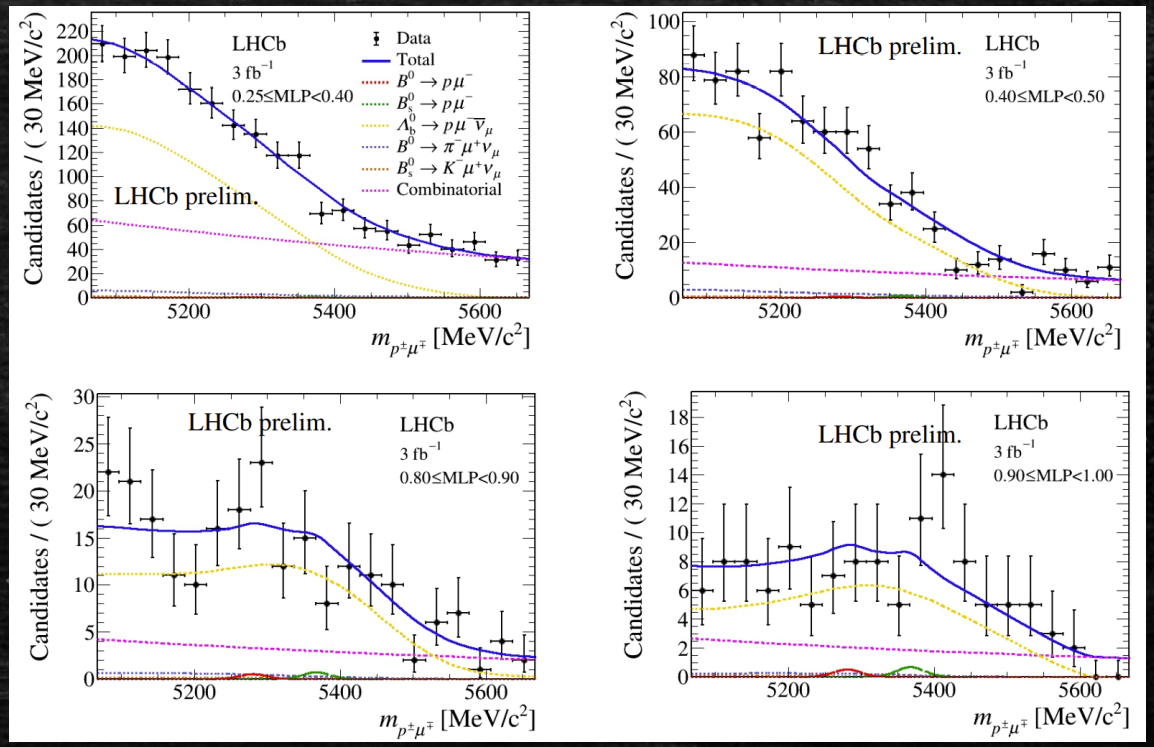
- $B^0_{(s)} \to p\mu^-$ (LHCb-PAPER-2022-022, in prep.)
  - Using $B^+ \to J/\psi(\mu^+\mu^-)K^+$ as normalization channel
  - Multilayer perceptron (MLP) classifier is used to separate signal and combinatorial background
- No evidence of signal decays
  - $Br(B^0_s \to p\mu^-) < 1.4 \times 10^{-8}$ @95% CL
  - $Br(B^0 \to p\mu^-) < 3.1 \times 10^{-9}$ @95% CL

First search on this decay mode!



Run1 + Run2





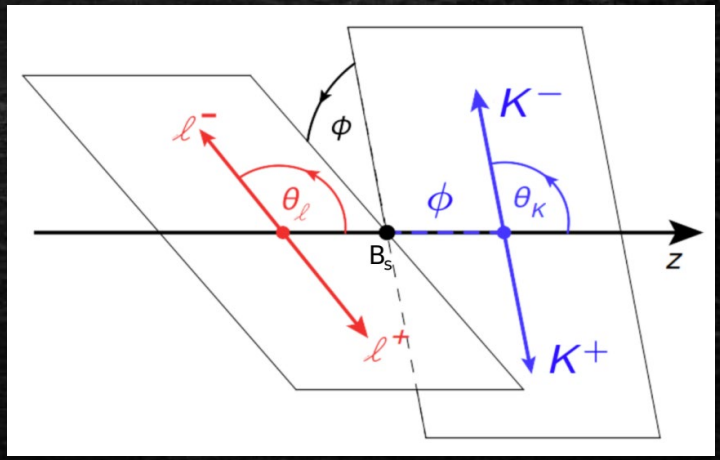
Searching deviation in decay phase spaces

Angular observables

- Observables sensitive to Wilson Coefficient in q^2 bins:

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_l\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K(1+\frac{1}{3}\cos 2\theta_l)$$
$$+F_{\mathrm{L}}\cos^2\theta_K(1-\cos 2\theta_l)$$
$$+S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_l\cos\phi$$
$$+A_5\sin 2\theta_K\sin\theta_l\cos\phi + \frac{4}{3}A_{\mathrm{FB}}^{CP}\sin^2\theta_K\cos\theta_l$$
$$+S_7\sin 2\theta_K\sin\theta_l\sin\phi + A_8\sin 2\theta_K\sin 2\theta_l\sin\phi$$
$$+A_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big] \qquad (9)$$

- F_L: longitudinal polarization fraction
- S_i: CP-averaged observables
- A_{FB}^{CP}: di-lepton forward-backward asymmetry



- "Clean" basis: cancellation of Form Factor at leading order

$$P_5' = S_5/\sqrt{F_L(1-F_L)} \qquad P_2 = \frac{2}{3}A_{FB}^{CP}/(1-F_L)$$

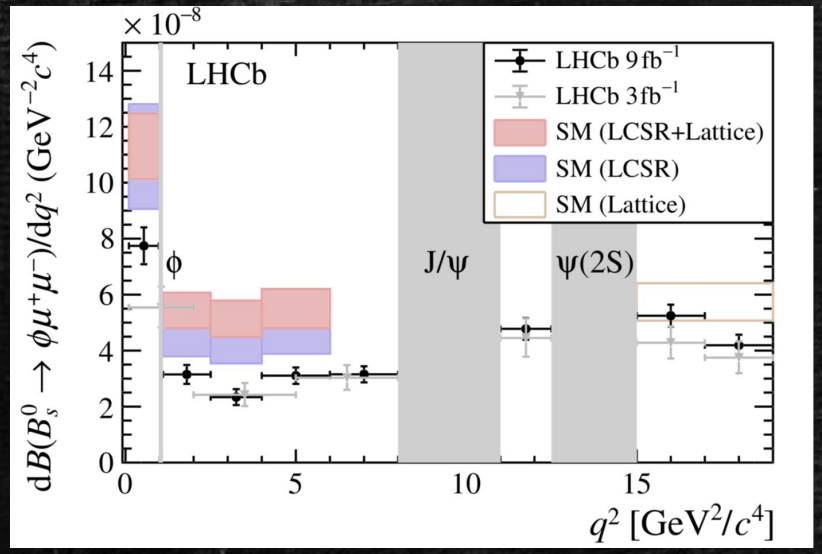
arXiv: 1207.2753

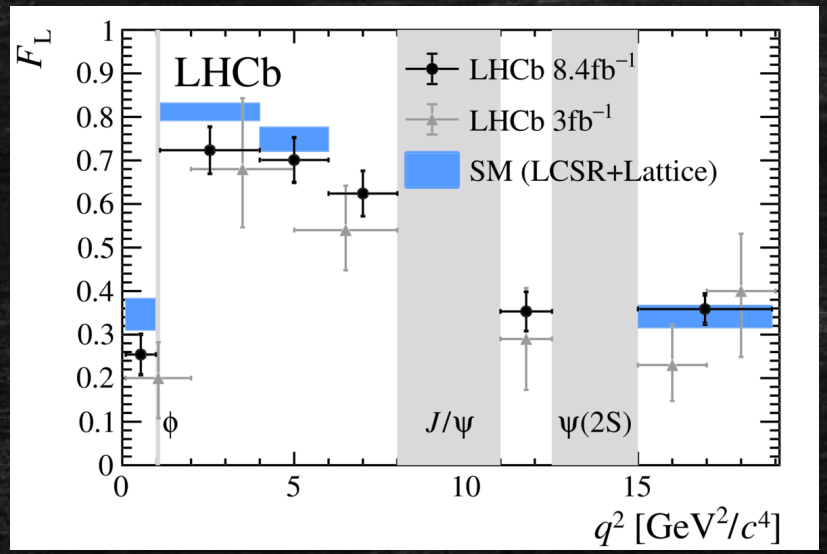
$B_s^0 \to \phi\mu^+\mu^-$

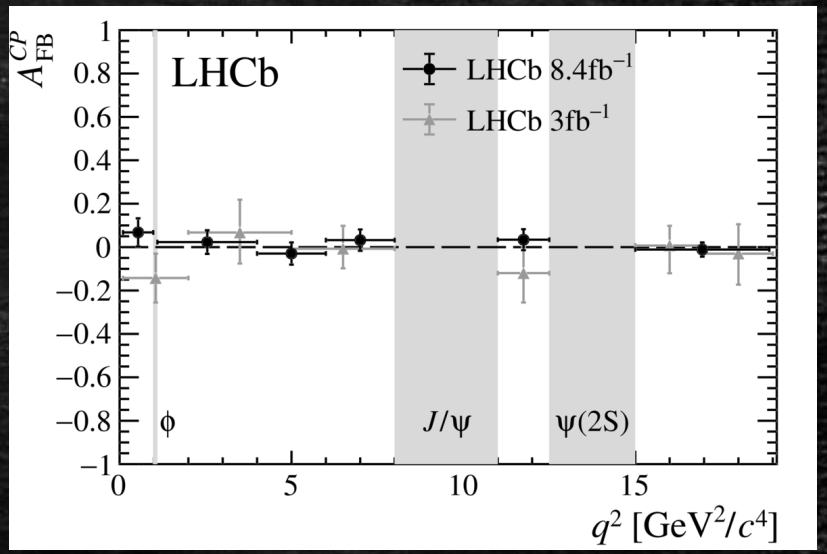
Run1 + Run2

PhysRevLett.127.151801 & JHEP11(2021)043

- Most precise differential branching fraction measurement of this decay in $q^2 \in [1.1, 6.0]\mathrm{GeV}^2/c^4$
  - 3.6σ below the SM prediction (LCSR+lattice), 1.8σ below the LCSR only prediction
  - Consistent with previous LHCb result
- Most precise angular observables measurement up to date





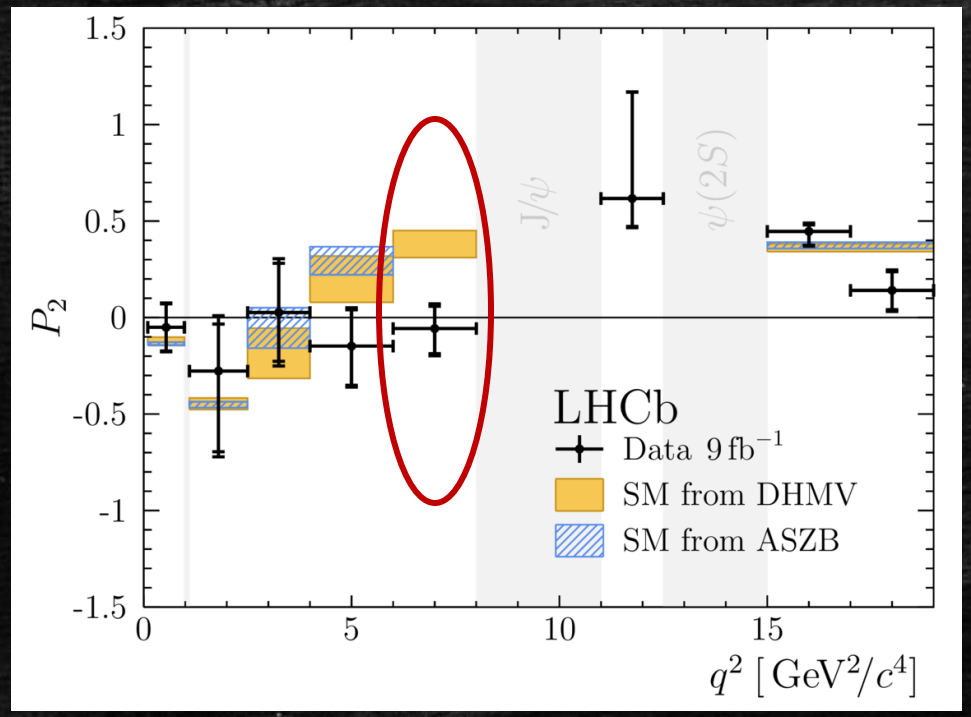


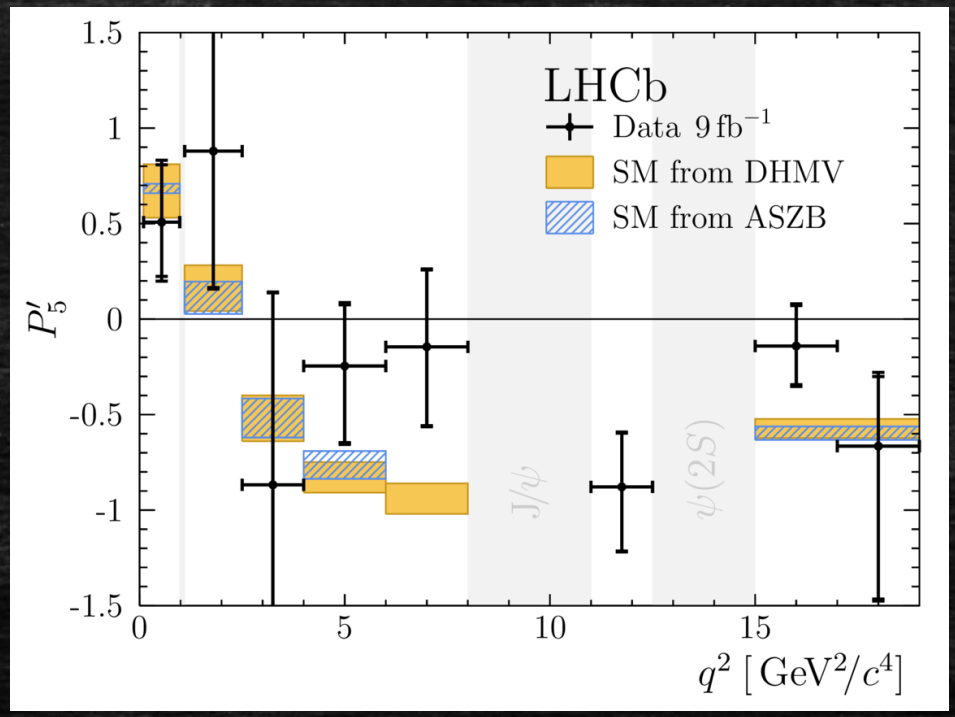
$B^+ \to K^{*+}\mu^+\mu^-$

Run1 + Run2

PhysRevLett.126.161802

- The full set of CP-average observables is measured in q^2 bins
- A **local deviation** of 3σ from the SM prediction is observed in P_2
  - The pattern of deviations consistent with previous measurement in isospin decay $B^0 \to K^{*0}\mu^+\mu^-$ (PhysRevLett.125.011802)
  - A_{FB} and F_L results are consistent with CMS (JHEP04(2021)124)





Testing Lepton Flavour Universality (LFU)

$B^+ \to K^+ l^+ l^-$ (R_K)

Run1 + Run2

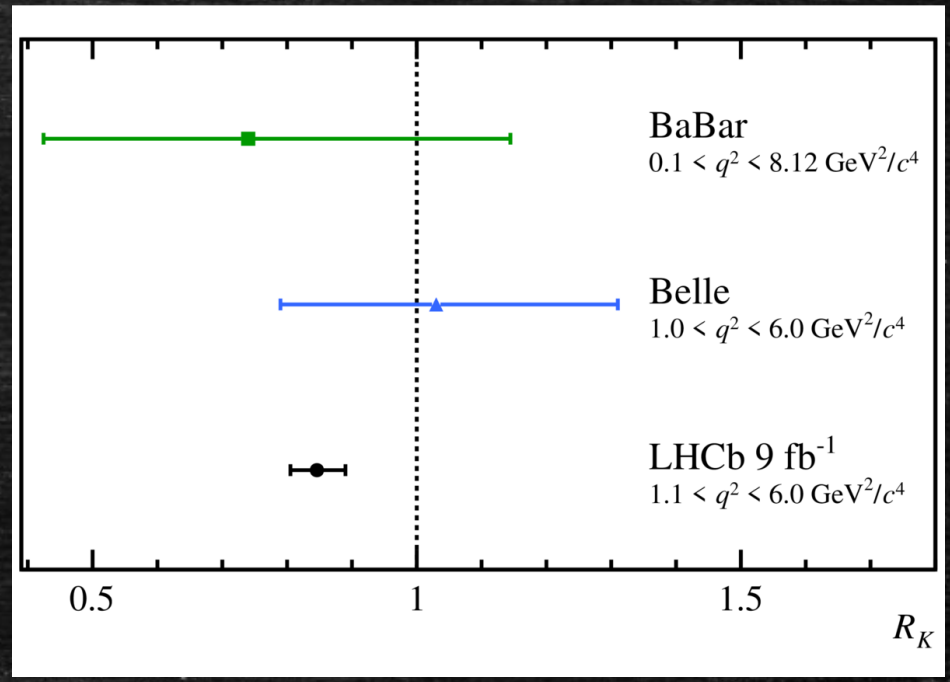
NaturePhys.18(2022)3

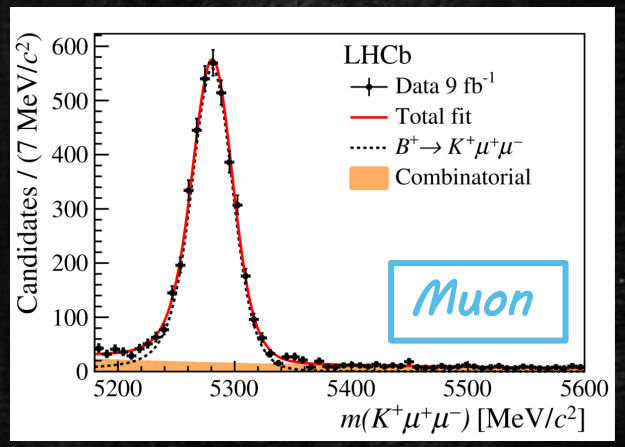
- Electroweak couplings are same for leptons in SM
  - AKA *Lepton Flavour Universality (LFU)*
- Measurement of R_K in $q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2/c^4$
  - Using double ratio to control systematics

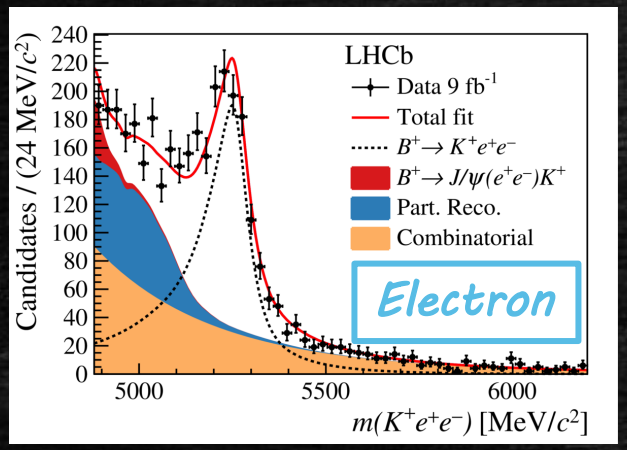
$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Big/ \frac{\mathcal{B}(B^+ \to K^+ e^+ e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)}.$$

- $R_K = 0.846^{+0.044}_{-0.041}$

3.1σ deviation from SM







$r_{J/\psi} = 0.981 \pm 0.020$ $R_{\psi(2S)} = 0.997 \pm 0.011$

Most precise LFU measurement in b→sll!

$B^+ \to K^{*+} l^+ l^-$ (R_{K^*}) and $B^0 \to K^0_S l^+ l^-$ $(R_{K^0_S})$

Run1 + Run2

PhysRevLett.128.191802

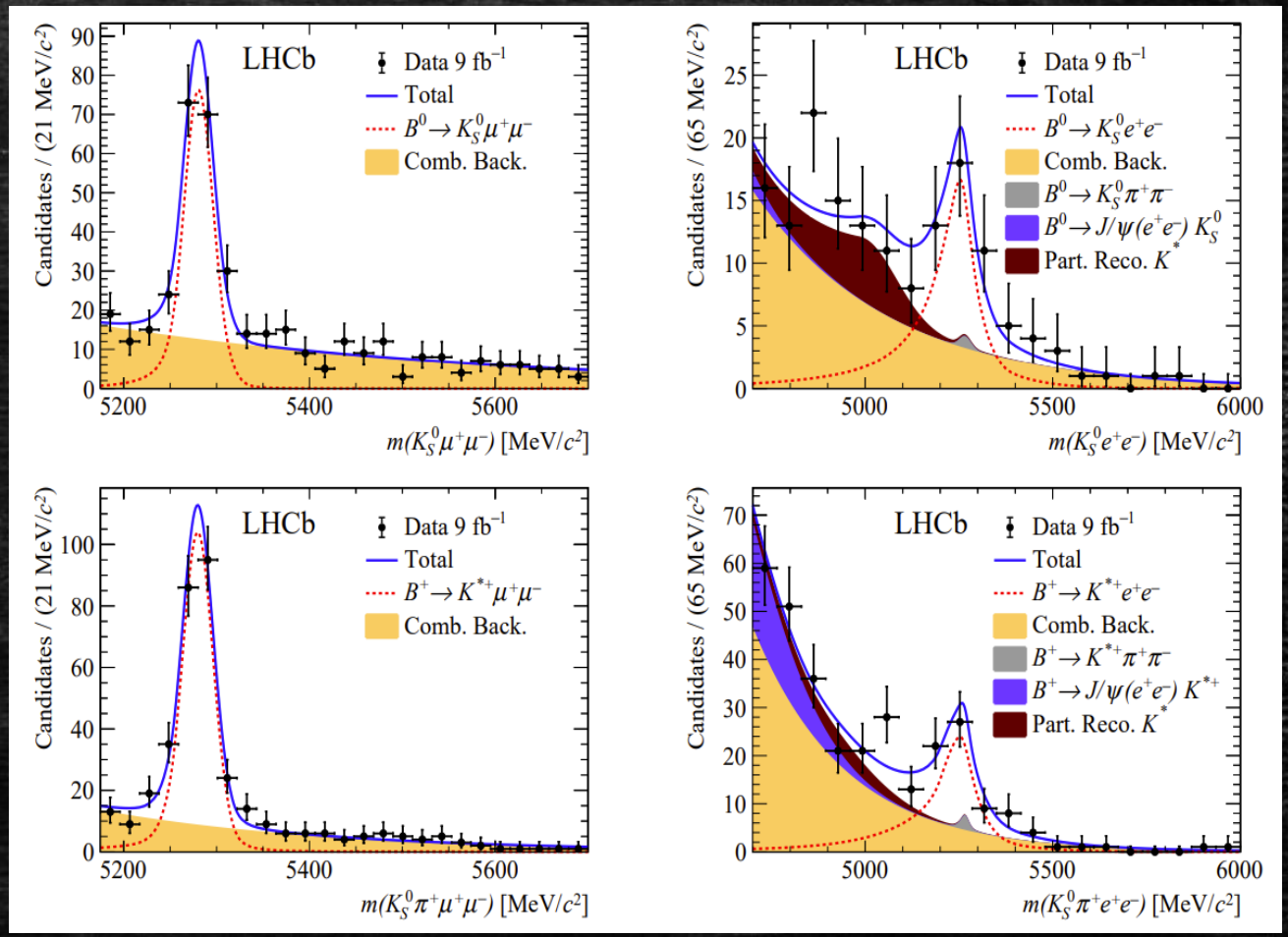
- Challenge in LHCb: long-lived particle $K^0_S \to \pi\pi$ reconstruction
  - Long tracks, decay outside vertex locator
  - Lower efficiency ⇒ low signal yields

$$R^{-1}_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)} e^+ e^-)}{\mathcal{B}(B \to J/\psi\,(e^+e^-)\,K^{(*)})} \Big/ \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to J/\psi\,(\mu^+\mu^-)\,K^{(*)})}$$

- Measurement results are consistent with SM within ~1.5σ

$$R_{K^0_S} = 0.66\,^{+0.20}_{-0.14}\,(\text{stat.})\,^{+0.02}_{-0.04}\,(\text{syst.})$$
$$R_{K^{*+}} = 0.70\,^{+0.18}_{-0.13}\,(\text{stat.})\,^{+0.03}_{-0.04}\,(\text{syst.})$$

First observation of electron mode!



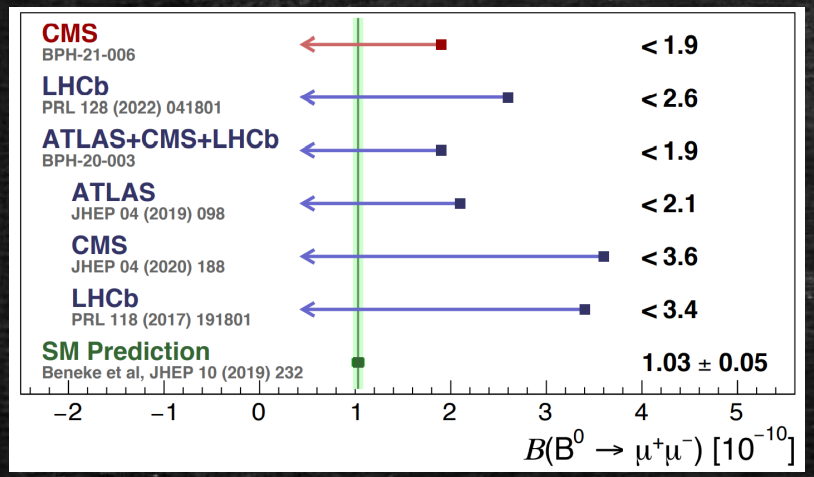
Summary

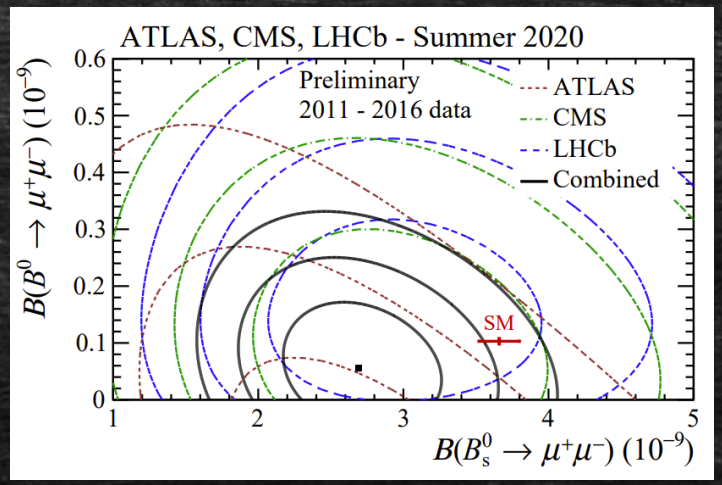
- Rare B decays and flavour anomalies provide stringent tests of New physics
- LHCb has already done tests based on Run1 and Run2 data sample
  - No significant deviation is observed yet :(
- Updates with more data and new modes are under development
  - With full Run1 and Run2 data sample
    - LFU: R_{pK}, R_{ϕ}, $R_{K\pi\pi}$...
    - LFV/LNV: $\Lambda_b^0 \to \Lambda(1520)\mu^{\pm}e^{\mp}$, $B^+ \to K^+e^{\pm}\mu^{\mp}$...
    - Angular observables: $B^+ \to K^+e^+e^-$, $B^0 \to K^{*0}e^+e^-$...
  - Run3 has started
    - Expected to accumulate ~23 fb^{-1} data at the end of Run3

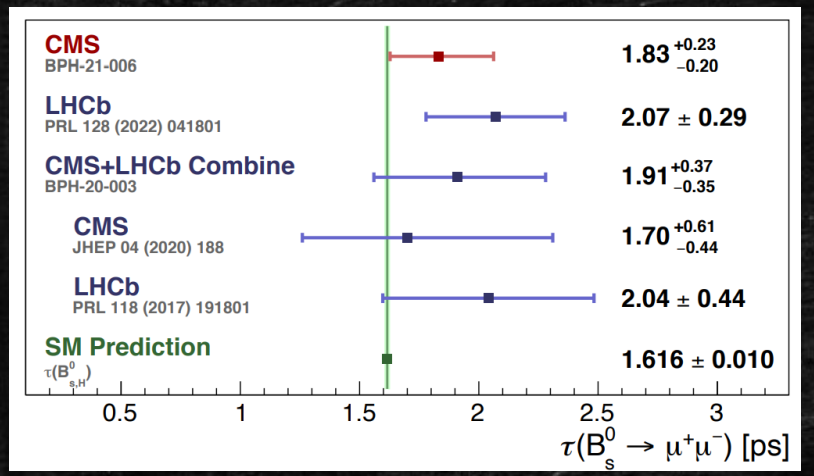
Stay tuned

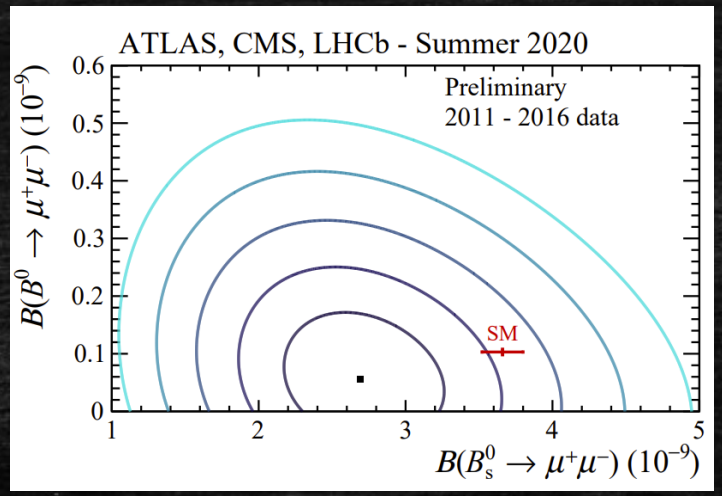
Back up

Combined result of $B^0_{(s)} \to \mu^+\mu^-$ ATLAS-CONF-2020-049









R_K

- $r_{J/\psi}$ in different phase spaces.