Overview of rare decays at LHCb

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on behalf of the LHCb Collaboration

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FSP LHCb
Erforschung von
Universum und Materie

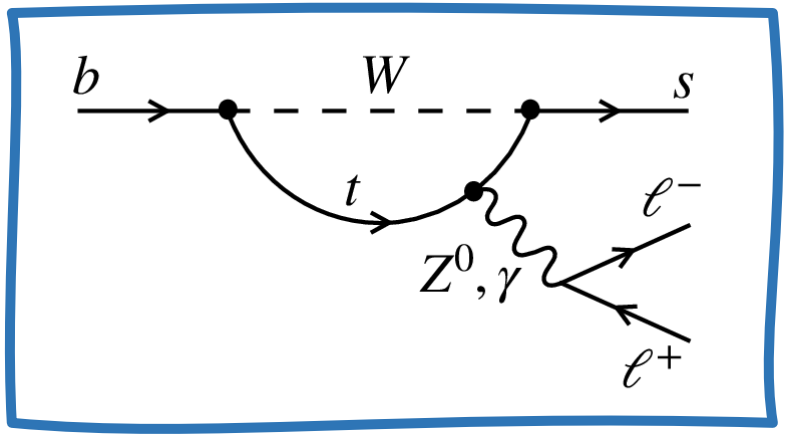
UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

IMPRS
for Precision Tests of
Fundamental Symmetries
INTERNATIONAL MAX PLANCK
RESEARCH SCHOOL

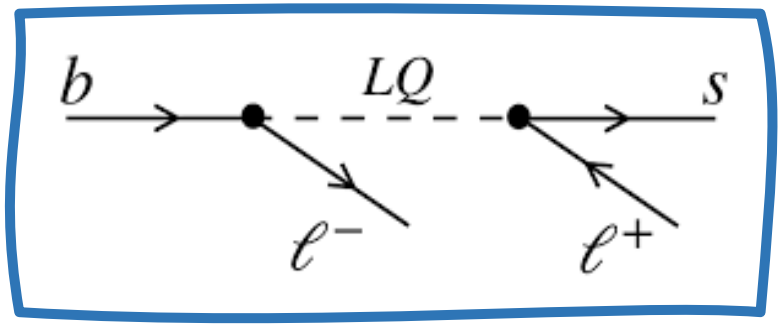
Rare decays

- Processes forbidden in the Standard Model (SM) at tree level
  - **Flavour Changing Neutral Current** (FCNC) decays only occur via electroweak penguin or box diagrams ⟹ strongly suppressed
  - Contribution from **New Physics** (NP) can affect branching fractions (BF), angular distributions, universality violation …
- Precision measurements of rare decays ⟹ **indirect search for NP**
- At **LHCb**
  - Electroweak penguin decays like $b \to s l^+ l^-$ transitions
    - Lepton Flavour Universality (LFU) tests ⟹ R_K, R_{K^*}
  - Radiative decays
  - Very rare decays
    - Purely leptonic, Lepton Flavour (LFV) and Lepton Number Violating (LNV) processes
  - Charm decays

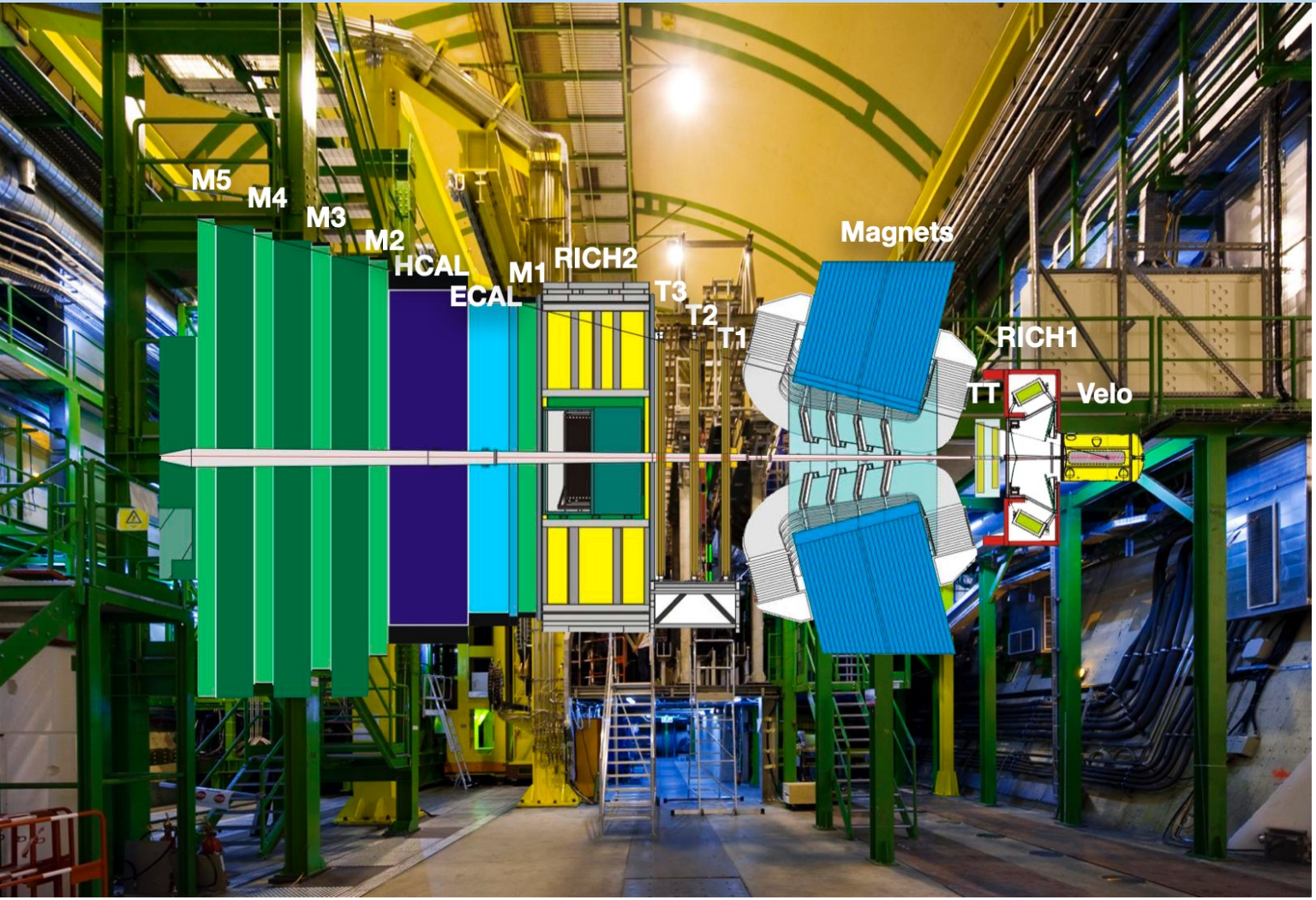
SM



NP



The LHCb detector



- Single arm forward spectrometer $(2 < \eta < 5)$
- Excellent **particle identification** from RICH(1,2), ECAL and Muon Stations
  - $\epsilon(e \to e) \sim 90\%$ and $\epsilon(h \to e) \sim 5\%$
  - $\epsilon(K \to K) \sim 95 - 97\%$ and $\epsilon(\pi \to K) \sim 5\%$
  - $\epsilon(\mu \to \mu) \sim 97\%$ and $\epsilon(\pi \to \mu) \sim 1 - 3\%$
- Good **tracking system**
  - $\Delta p/p = 0.5\%$ at low momentum
  - Impact parameter resolution $(15 + 29\ /p_T)\mu m$

	Run 1 (2011,2012)		Run 2 (2015-2018)
$\sqrt{s}$	7 TeV	8 TeV	13 TeV
$\int \mathcal{L}\, dt$	1.0 fb^{-1}	2.0 fb^{-1}	~6 fb^{-1}

[2008 JINST 3 S08005], [arXiv:1306.0249]

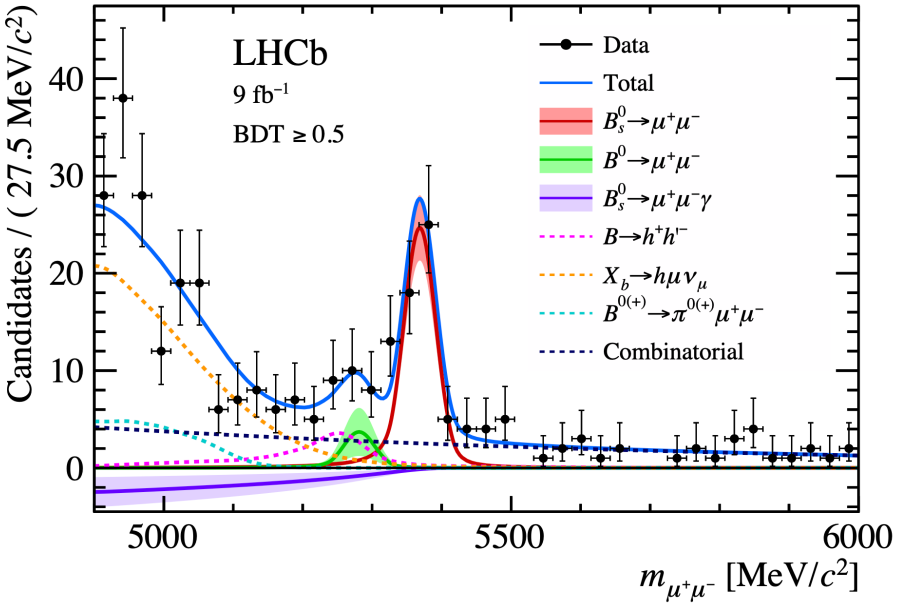
$B^0_{(s)} \to \mu^+\mu^-$

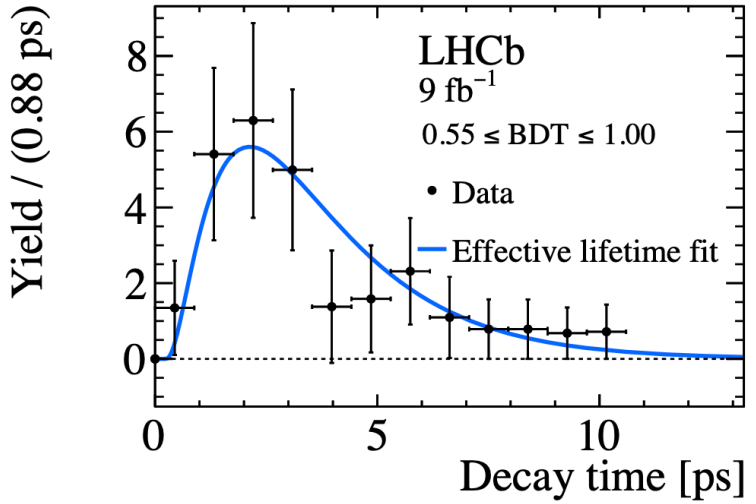
PRL 128 (2022) 041801, PRD 105 (2022) 012010

Run1+Run2 dataset

- FCNC + helicity suppressed
  - SM deviations could reveal existance of new particles (Z', LQ, …)
- **Results in agreement with SM** predictions within 2σ
- **Measurement of**
  - $\mathcal{B}(B^0_s \to \mu^+\mu^-) = 3.09^{+0.46\ +0.15}_{-0.43\ -0.11} \times 10^{-9}$
    - Excess of 10σ from background
  - $\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6\times10^{-10}$ @ 95% CL
    - **Most stringent limit** up to date

Most precise measurement from CMS (more here) $2.69^{+0.37}_{-0.35}\times10^{-9}$





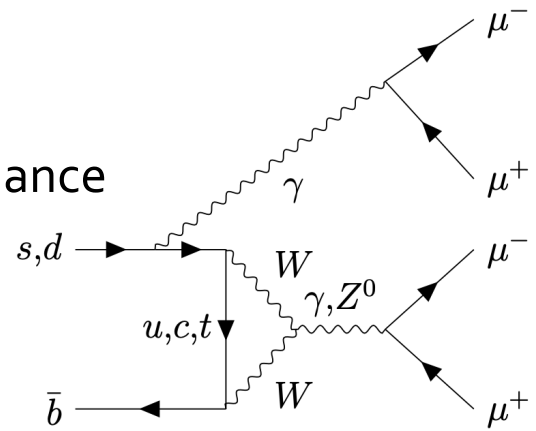
- Measurement of $B^0_s \to \mu^+\mu^-$ **effective lifetime** superseding previous result
  - $\tau(B^0_s \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03\ ps$
  - Outside the range of light ($\tau_L = 1.432 \pm 0.005\ ps$) and high ($\tau_H = 1.620 \pm 0.007\ ps$) eigenstates
- **First search** for $B^0_s \to \mu^+\mu^-\gamma$
  - $\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\ \mathrm{GeV/c^2}} < 2.0\times10^{-9}$ @ 95% CL

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

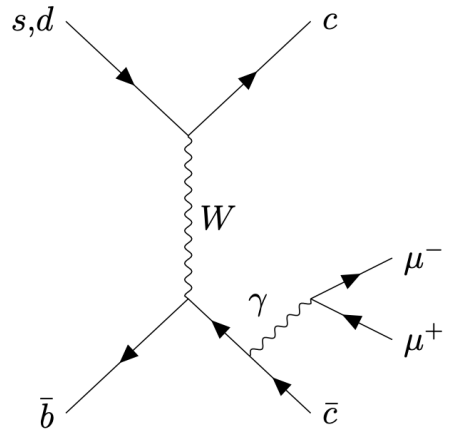
JHEP 03 (2022) 109

Run1+Run2 dataset

- Highly suppressed in the SM
  - $\sim 10^{-10}$ for the B^0_s mode and $\sim 10^{-12}$ for the B^0 mode
- Rate enhanced in **BSM theories** with light narrow scalar resonance
- Search for
  - **Non resonant mode** (new wrt to Run 1)
  - $\boldsymbol{B^0_{(s)} \to a(\mu^+\mu^-)a(\mu^+\mu^-)}$: assuming $m_a = 1\ GeV/c^2$
  - $\boldsymbol{B^0_{(s)} \to J/\psi(\mu^+\mu^-)\mu^+\mu^-}$: $\sim 10^{-13} - 10^{-11}$ in SM



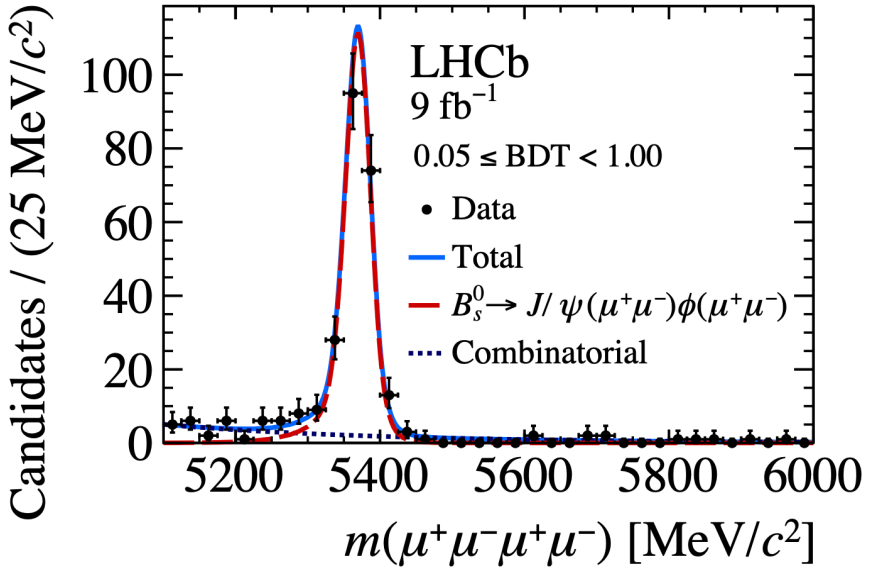
$B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$



$B^0_s \to J/\psi(\mu^+\mu^-)\mu^+\mu^-$

- $B^0_s \to J/\psi(\mu^+\mu^-)\phi(\mu^+\mu^-)$ used as **normalisation channel**

- **Background rejection**
  - $B^0_s \to J/\psi(\mu^+\mu^-)\phi(\mu^+\mu^-)$ and $B^0_s \to \phi(\mu^+\mu^-)\phi(\mu^+\mu^-)$ suppressed by J/ψ and ϕ vetoes
  - PID selection to reduce misID background from *b*-hadron decays



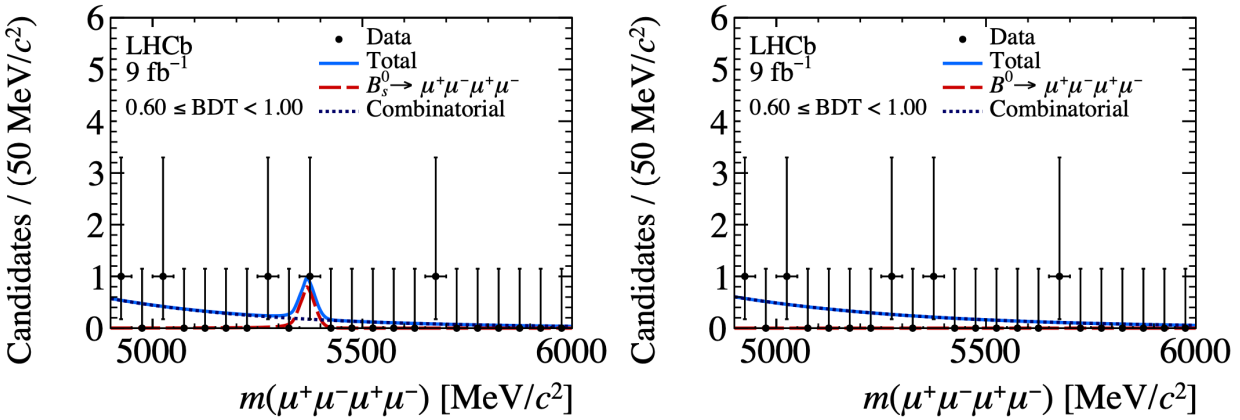
$B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$

JHEP 03 (2022) 109

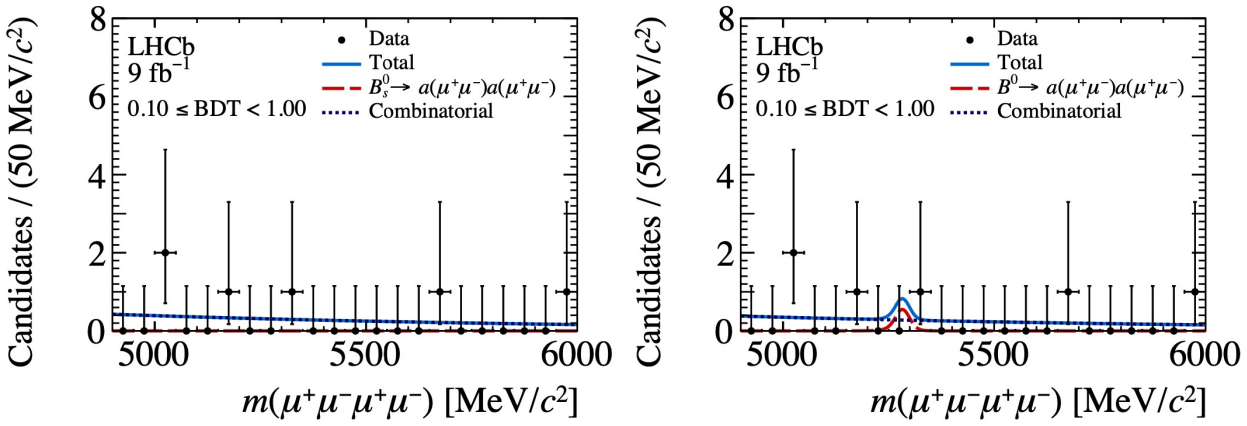
Run1+Run2 dataset

- No significant signal observed
- **Most stringent limits** up to date set @ 95% CL
  - $\mathcal{B}(B^0_s \to \mu^+\mu^-\mu^+\mu^-) < 8.6\times10^{-10}$
  - $\mathcal{B}(B^0 \to \mu^+\mu^-\mu^+\mu^-) < 1.8\times10^{-10}$
  - $\mathcal{B}(B^0_s \to a(\mu^+\mu^-)a(\mu^+\mu^-)) < 5.8\times10^{-10}$
  - $\mathcal{B}(B^0 \to a(\mu^+\mu^-)a(\mu^+\mu^-)) < 2.3\times10^{-10}$
  - $\mathcal{B}(B^0_s \to J/\psi(\mu^+\mu^-)\mu^+\mu^-) < 2.6\times10^{-9}$
  - $\mathcal{B}(B^0 \to J/\psi(\mu^+\mu^-)\mu^+\mu^-) < 1.0\times10^{-9}$

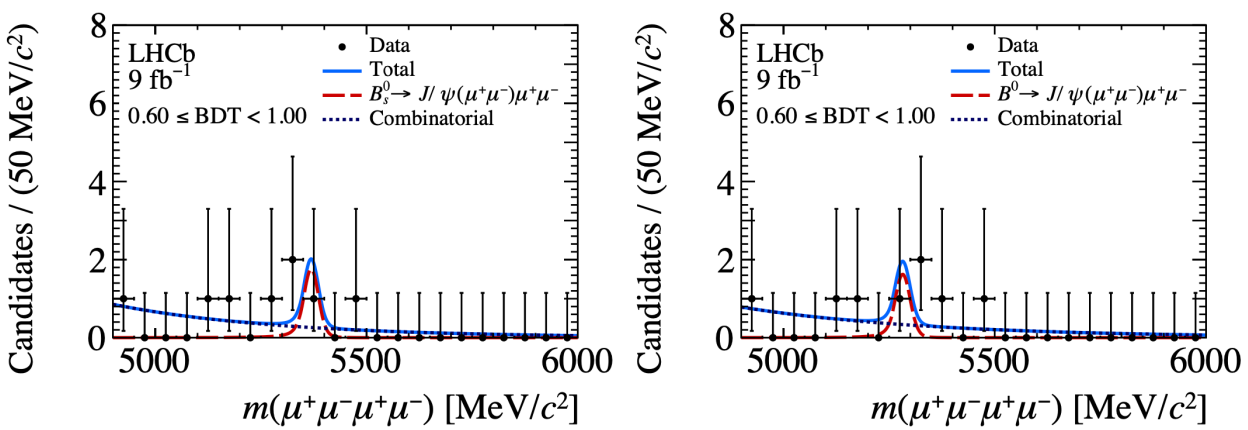
$B^0_{(s)} \to \mu^+\mu^-\mu^+\mu^-$



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



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



Lepton Universality

Nat. Phys. 18 (2022) 277-282

Run1+Run2 dataset

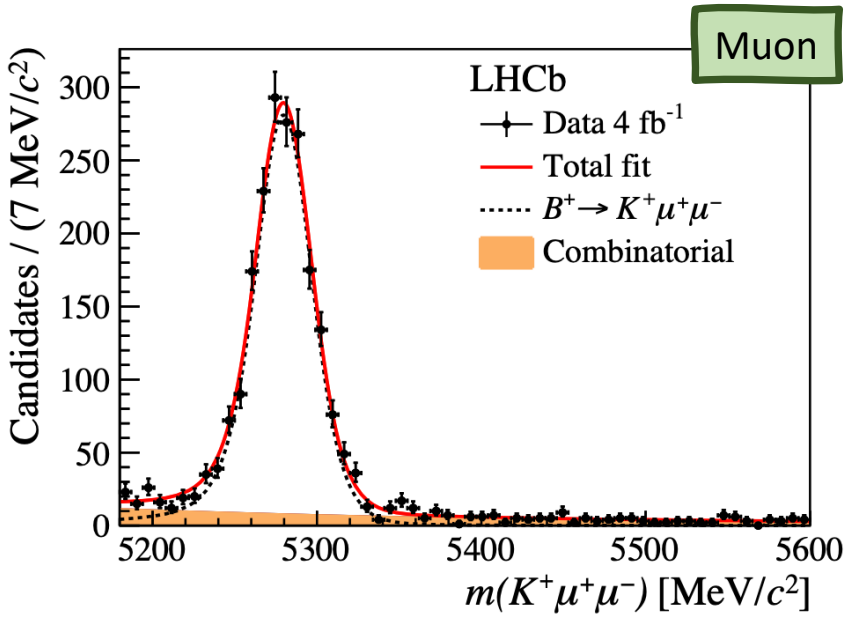
- The SM predicts same electroweak couplings for all the three lepton flavours
  $\Longrightarrow$ **Lepton Flavour Universality** (FLU)
- Extensions to SM predict new virtual particles contributing to b $\rightarrow$ s transitions and have nonuniversal interactions
  $\Longrightarrow$ $\boldsymbol{b \rightarrow s\, l^+ l^-}$ transitions as **probe for LFU**

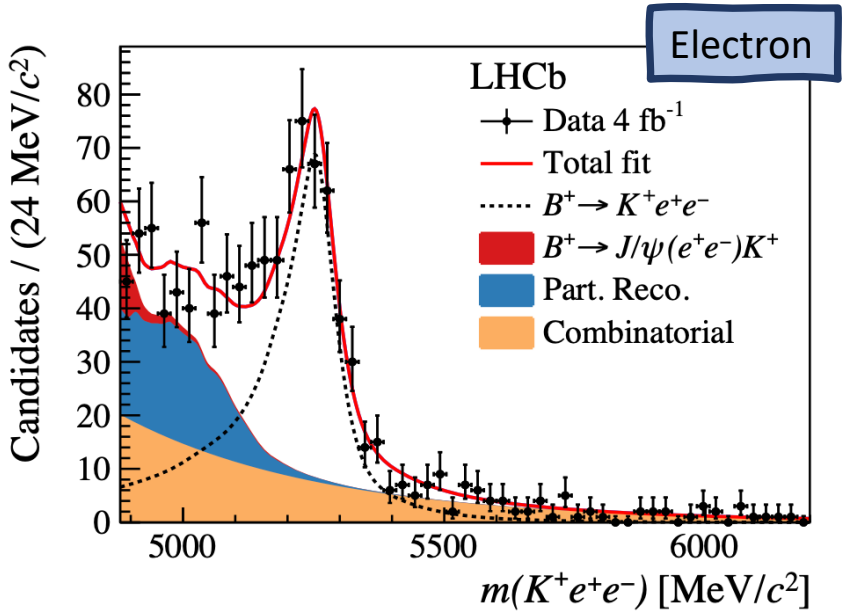
$$\frac{\Gamma(Z \rightarrow \mu^+\mu^-)}{\Gamma(Z \rightarrow e^+e^-)} = 1.0001 \pm 0.0024$$

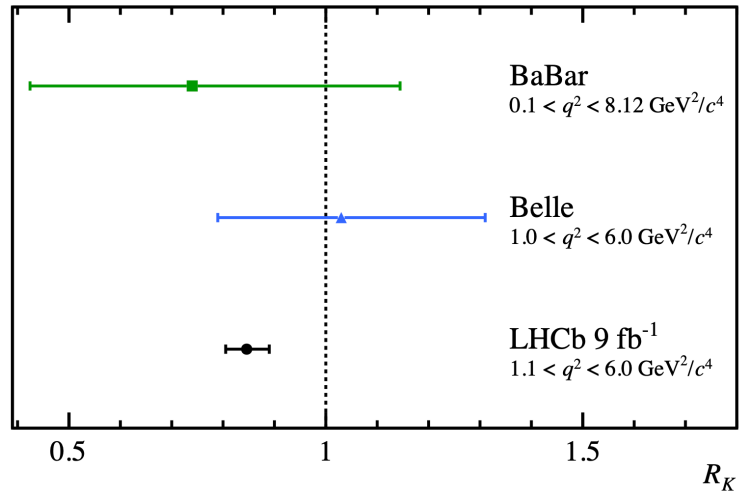
$$\frac{\Gamma(W \rightarrow \mu\, \nu_\mu)}{\Gamma(W \rightarrow e\, \nu_e)} = 0.996 \pm 0.008$$

- Measurement of $R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} \times \frac{\mathcal{B}(B^+ \rightarrow J/\psi(e^+e^-)K^+)}{\mathcal{B}(B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+)}$ in $q^2 \in [1.1, 6.0]\ \mathrm{GeV}^2/c^4$

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







Deviation of 3.1σ from SM

Lepton Universality

PRL 128 (2022) 191802

Run1+Run2 dataset

- Study of the isospin partners

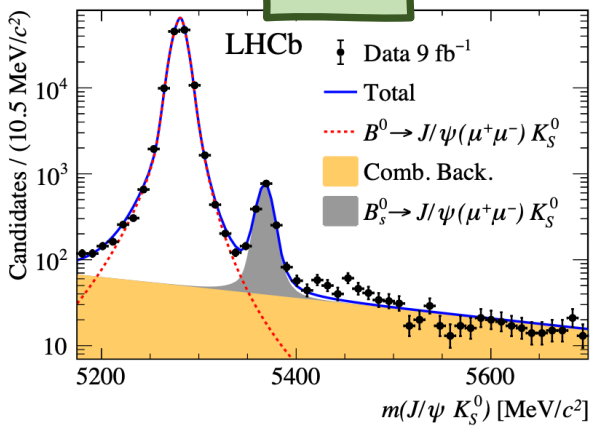
  $B^0 \to K_S^0 l^+ l^-$ and $B^+ \to K^{*+} l^+ l^-$

- Resonant modes as control channels

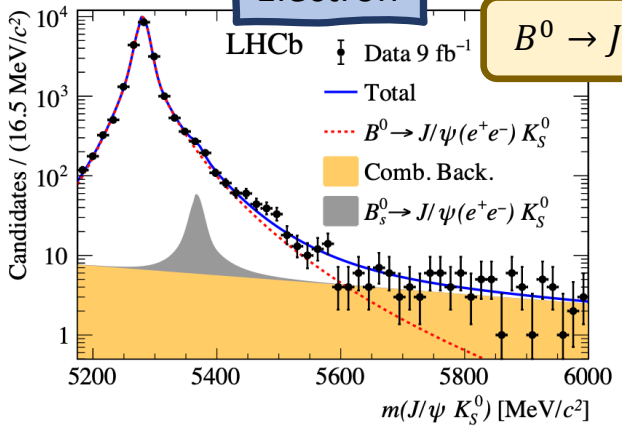
$$R^{-1}_{K^0_S} = \frac{\mathcal{B}(B^0 \to K^0_S e^+ e^-)}{\mathcal{B}(B^0 \to K^0_S \mu^+ \mu^-)} \times \frac{\mathcal{B}(B^0 \to J/\psi(\mu^+\mu^-) K^0_S)}{\mathcal{B}(B^0 \to J/\psi(e^+e^-) K^0_S)} \text{ in } q^2 \in [1.1, 6.0]\ \text{GeV}^4/c^2$$

$$R^{-1}_{K^{*+}} = \frac{\mathcal{B}(B^+ \to K^{*+} e^+ e^-)}{\mathcal{B}(B^+ \to K^{*+} \mu^+ \mu^-)} \times \frac{\mathcal{B}(B^+ \to J/\psi(\mu^+\mu^-) K^{*+})}{\mathcal{B}(B^+ \to J/\psi(e^+e^-) K^{*+})} \text{ in } q^2 \in [0.045, 6.0]\ \text{GeV}^4/c^2$$

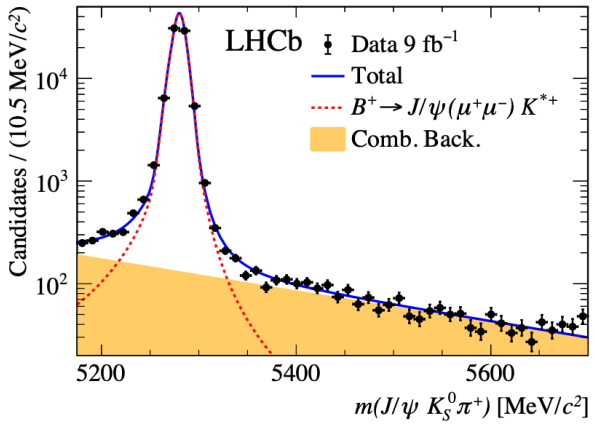
Muon

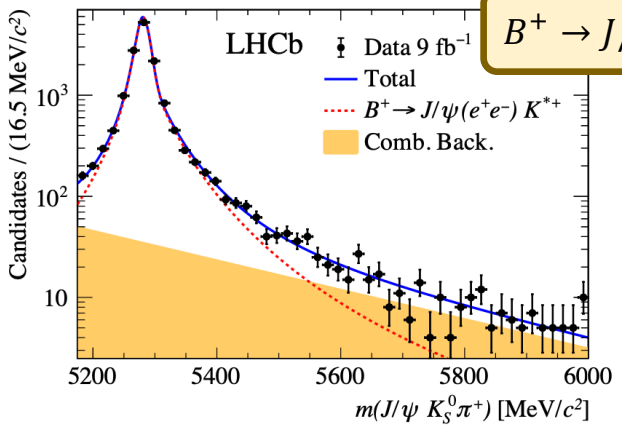


Electron



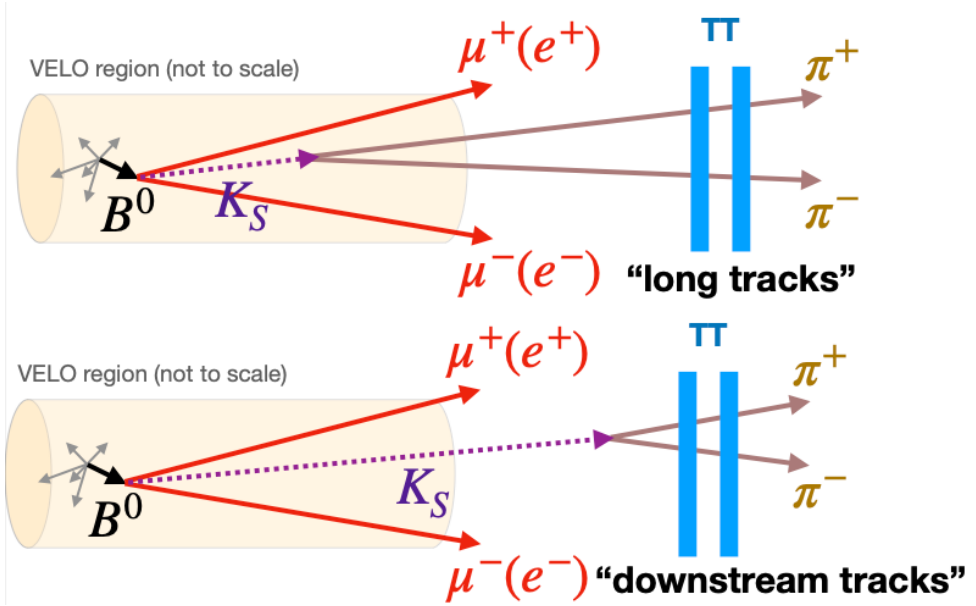
$B^0 \to J/\psi(l^+l^-)K^0_S$





$B^+ \to J/\psi(l^+l^-)K^{*+}$

- Long lived K^0_S in the final state reducing experimental efficiency
- K^0_S reconstruction



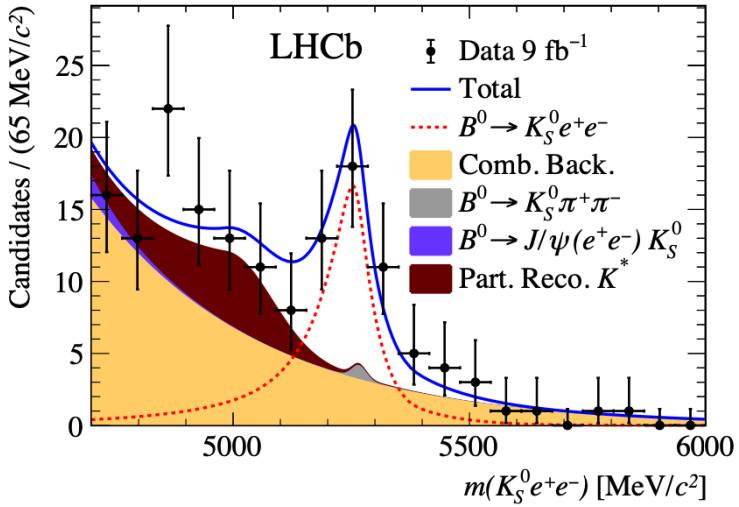
Lepton Universality

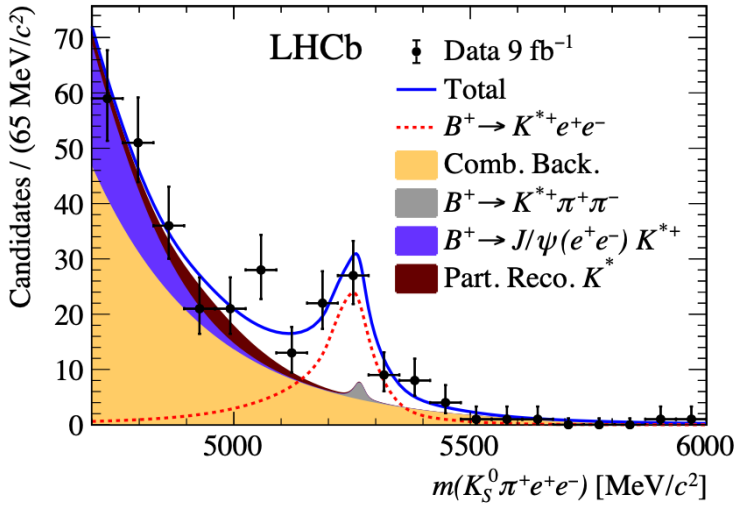
PRL 128 (2022) 191802

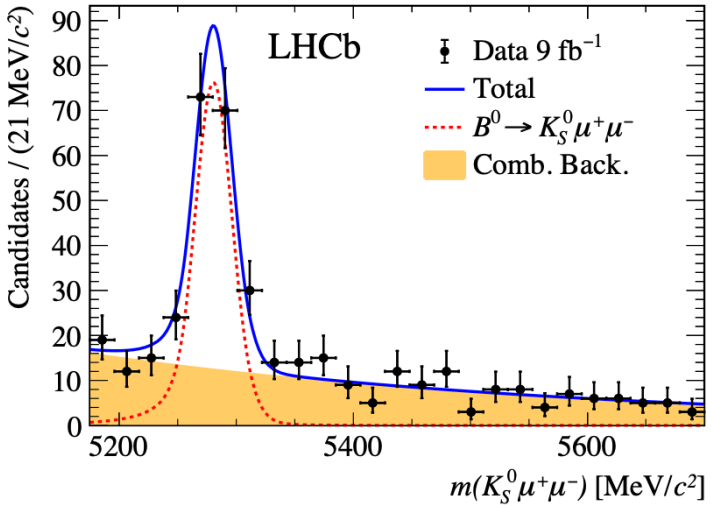
Run1+Run2 dataset

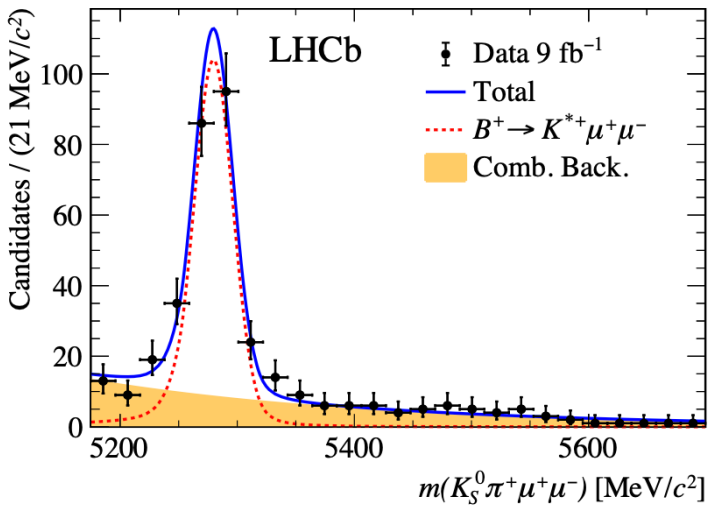
$$R^{-1}_{K^0_S} = 1.51\ ^{+0.40}_{-0.35}(\text{stat.})\ ^{+0.09}_{-0.04}(\text{syst.})$$
$$R_{K^0_S} = 0.66\ ^{+0.20}_{-0.14}(\text{stat.})\ ^{+0.02}_{-0.04}(\text{syst.})$$

$$R^{-1}_{K^{*+}} = 1.44\ ^{+0.32}_{-0.29}(\text{stat.})\ ^{+0.09}_{-0.06}(\text{syst.})$$
$$R_{K^{*+}} = 0.70\ ^{+0.18}_{-0.13}(\text{stat.})\ ^{+0.03}_{-0.04}(\text{syst.})$$

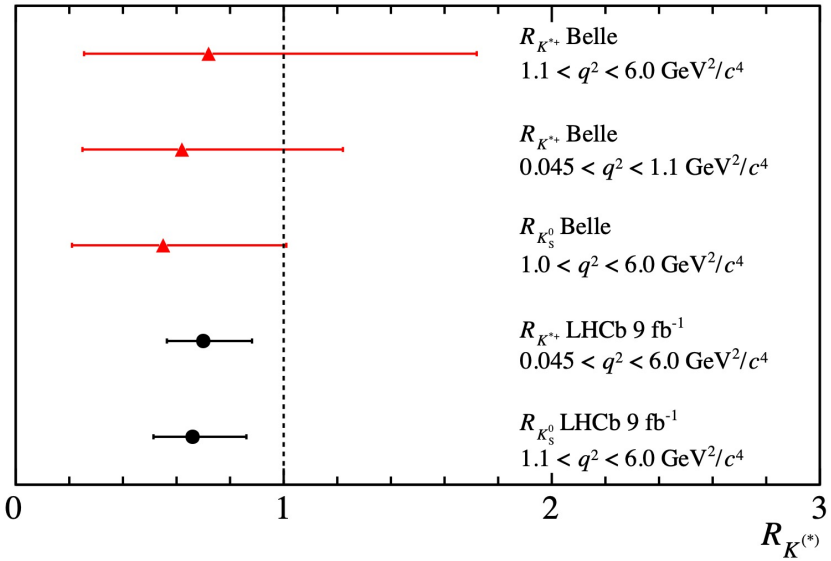








- $R^{-1}_{K^0_S}$ and $R^{-1}_{K^{*+}}$ consistent with SM at 1.5σ and 1.4σ



- **Same deficit of muonic wrt electronic decays observed in other LHCb LFU tests like R_{K^*} (JHEP08(2017)055) and R_{pK} (JHEP05(2020)040)**

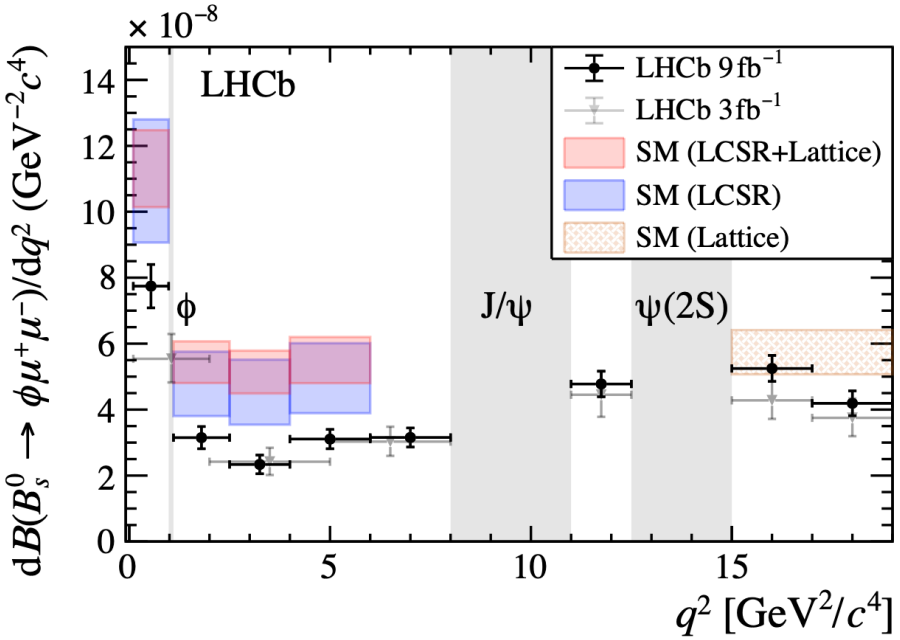
Marin Benito's talk Friday 9:30

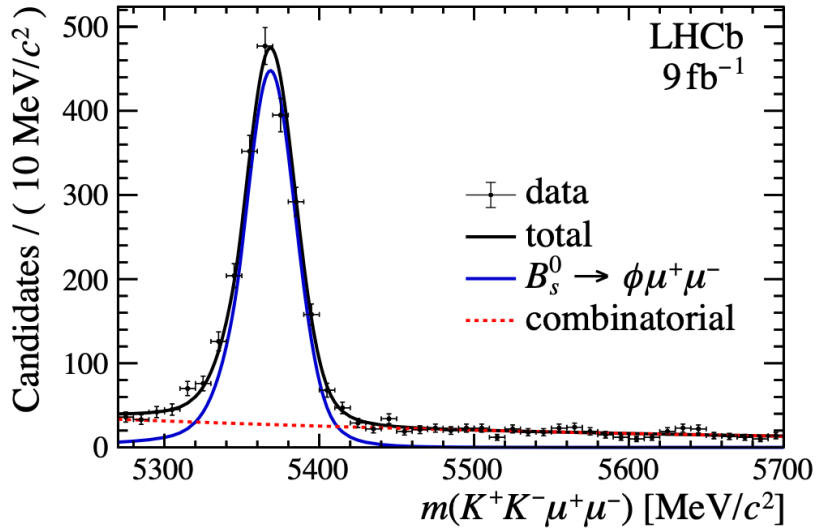
$B_s^0 \to \phi\mu^+\mu^-$

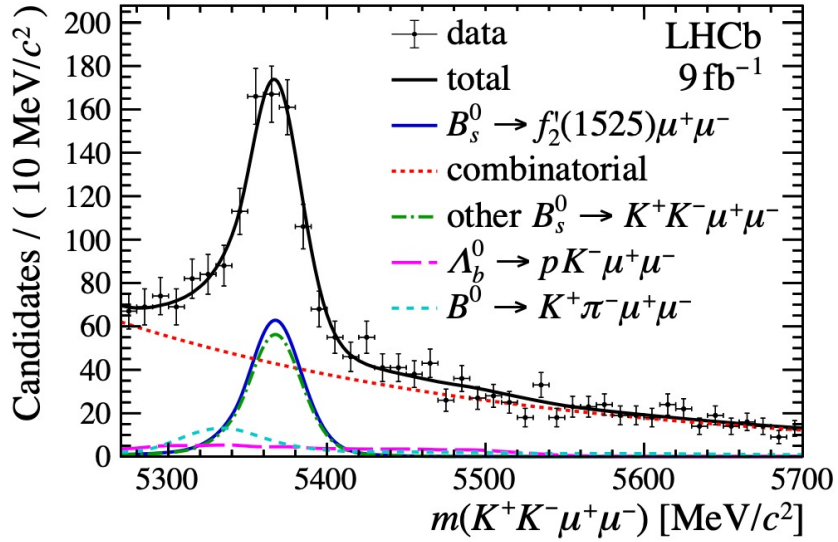
PRL 127 (2021) 151801

Run1+Run2 dataset

- Most precise measurement of the **differential BF** of $B_s^0 \to \phi\mu^+\mu^-$ in the q^2 region $[1.1, 6]$ GeV$^2/c^4$
- Multivariate classifier trained against combinatorial background
- 3.6σ below SM prediction (LCSR+lattice), 1.8σ below SM prediction (LCSR)







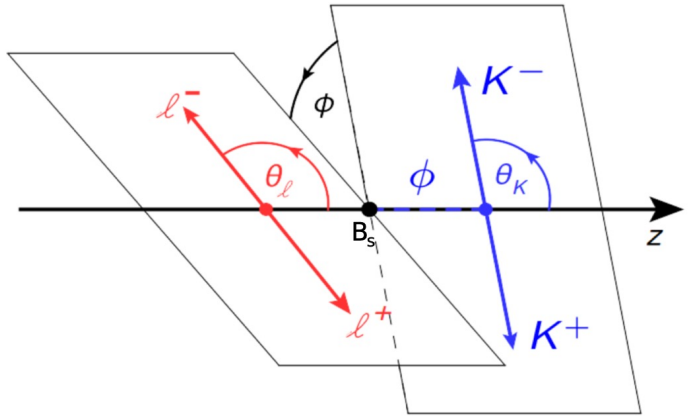
- Result in agreement with previous LHCb measurement
  - $\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (8.14 \pm 0.21 \pm 0.16 \pm 0.03 \pm 0.39) \times 10^{-7}$
- **First observation** of $B_s^0 \to f_2'(1525)\mu^+\mu^-$ decay
  - $\mathcal{B}(B_s^0 \to f_2'(1525)\mu^+\mu^-) = (1.57 \pm 0.19 \pm 0.06 \pm 0.06 \pm 0.08) \times 10^{-7}$

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

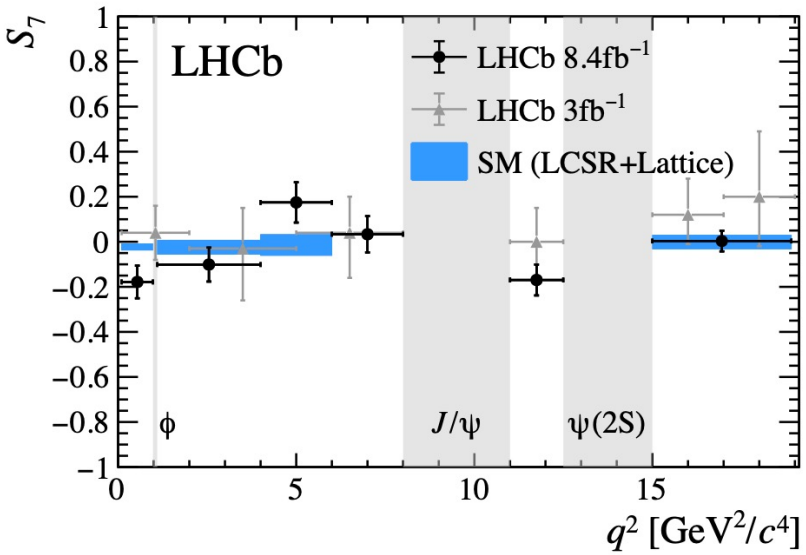
JHEP 11 (2021) 043

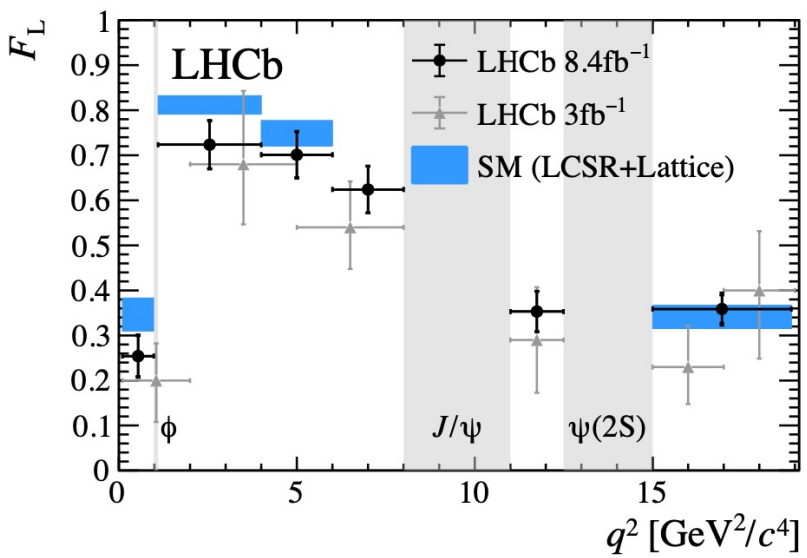
Run1+Run2 dataset

- **Angular analysis** complementary to BF measurement in probing NP contributions
- Most precise measurement of $B_s^0 \to \phi\mu^+\mu^-$ angular observables
  - ϕ reconstructed via $\phi \to K^+K^-$ decay
- Unbinned maximum likelihood fit to $m(KK\mu\mu)$, θ_l, θ_K and ϕ in q^2 bins

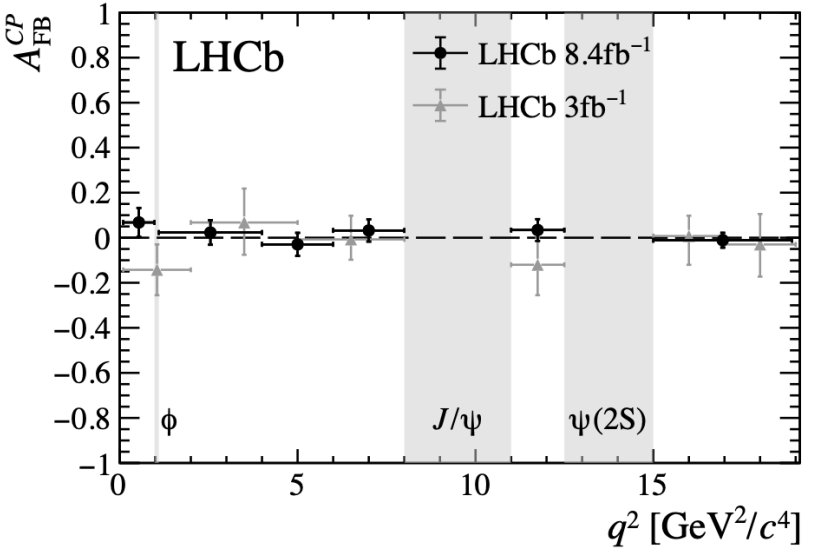


CP-averages observables





CP-asymmetry



- Angular observables compatible with SM predictions (no CP asymmetry)
  - CP averages: small deviation in F_L at low q^2
- Deviation consistent with results observed in $B^+ \to K^{*+}\mu^+\mu^-$ (PRL 126,161802(2021)) and $B^0 \to K^{*0}\mu^+\mu^-$ (PRL 125, 011802 (2020))

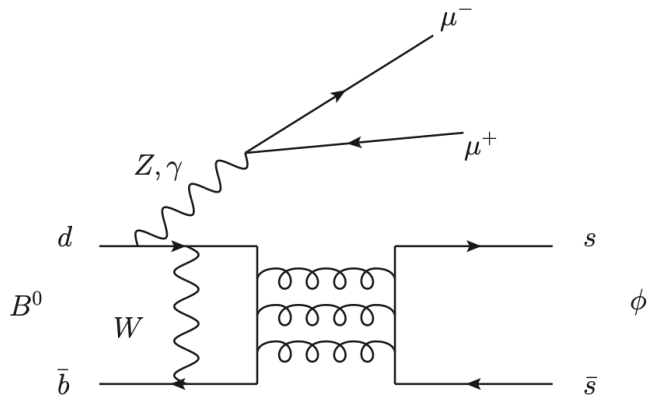
$B^0 \to \phi\mu^+\mu^-$

JHEP 05 (2022) 067

New | Run1+Run2 dataset

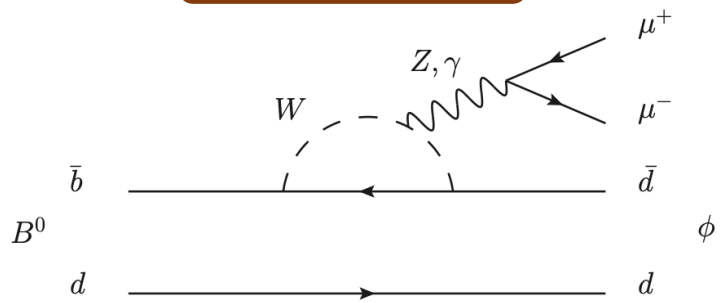
- Mainly proceeds via **color-suppressed penguin annihilation**
  - very suppressed in the SM ($\sim 10^{-12}$)
- Contributions from $\boldsymbol{\omega - \phi}$ **mixing**
  - enhances decay rate to $\sim 10^{-11} - 10^{-10}$ (accessible at HL-LHC)

Weak annihilation



- Measurement of $\mathcal{R} = \dfrac{\mathcal{B}(B^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}$

$\omega - \phi$ mixing



- Analysis strategy
  - $B_s^0 \to \phi\mu^+\mu^-$ used as **normalisation channel**
  - $B^0 \to J/\psi\phi$ used as **control channel** (more copious)
  - **Background sources**
    - Mass vetoes to suppress peaking background from misID ($B^0 \to J/\psi\,\phi$, $\Lambda_b \to pK^-\mu^+\mu^-$)
    - Multivariate classifier (BDT) trained to reduce combinatorial background

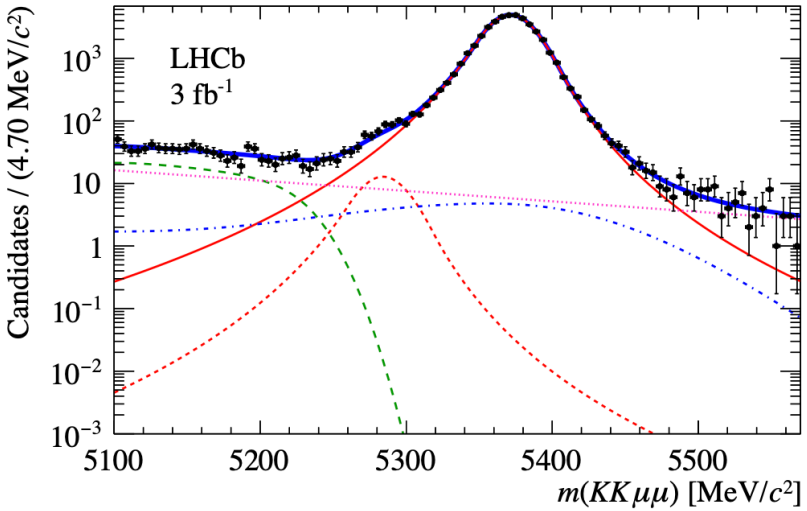
$B^0 \to \phi\mu^+\mu^-$

JHEP 05 (2022) 067

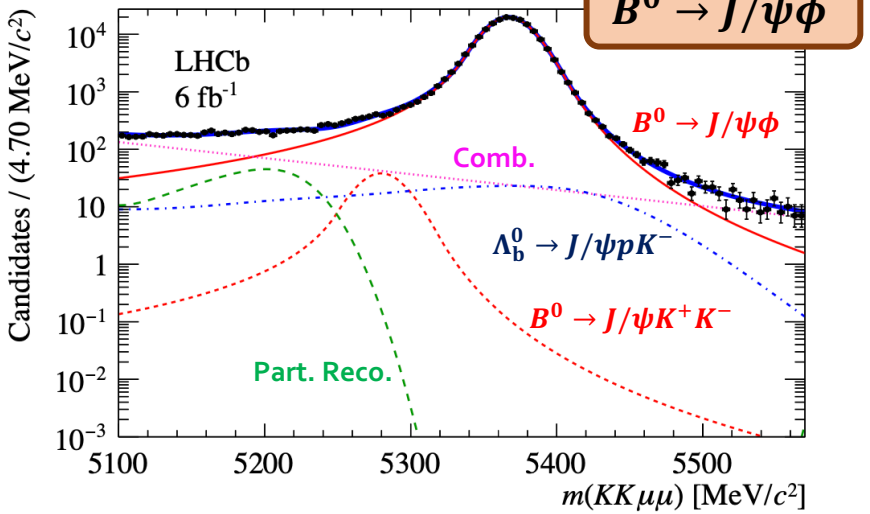
New | Run1+Run2 dataset

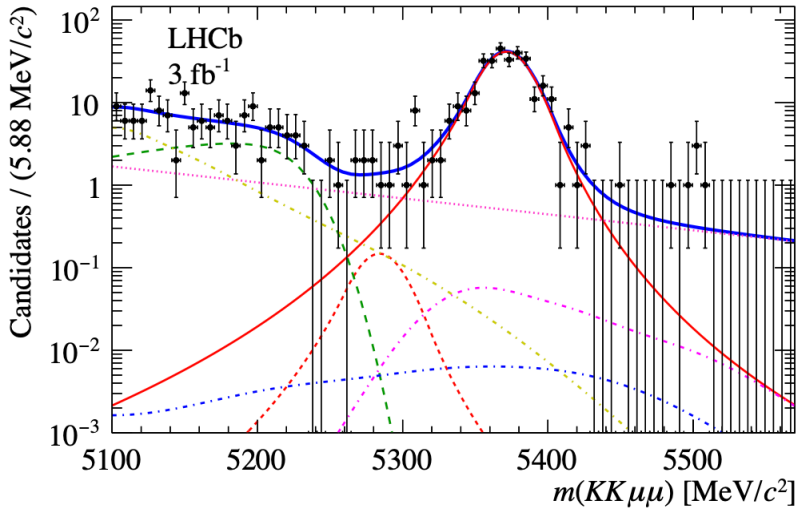
LHCb

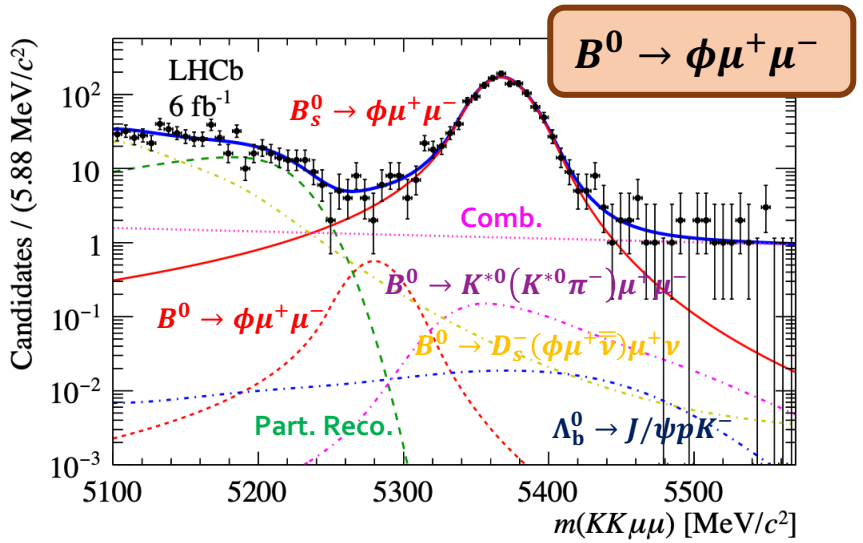
Run 1



Run 2







- No significant signal observed
- Excluding ϕ and charmonium region in dimuon spectrum

$$\mathcal{R} < 4.4\times10^{-3} \text{ @ } 90\%\ CL$$

- Assuming phase-space model

$$\mathcal{B} < 3.2\times10^{-9} \text{ @ } 90\%\ CL$$

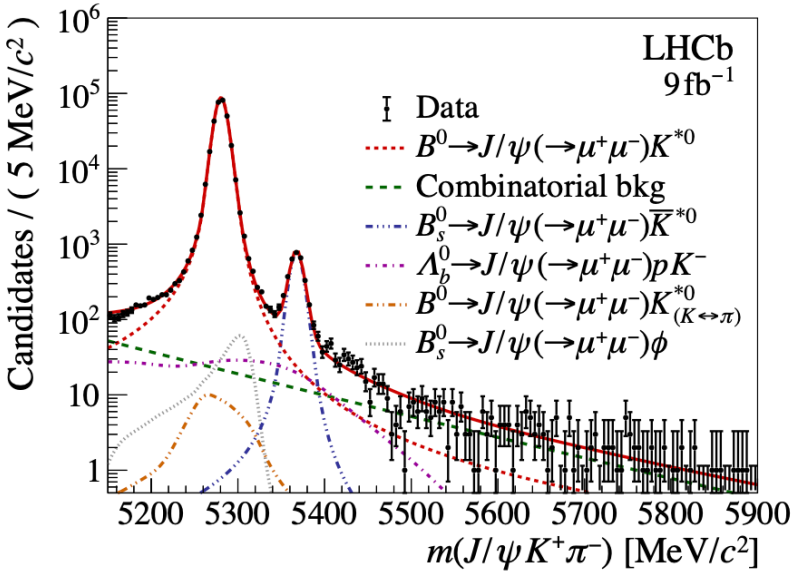
in full q^2 region

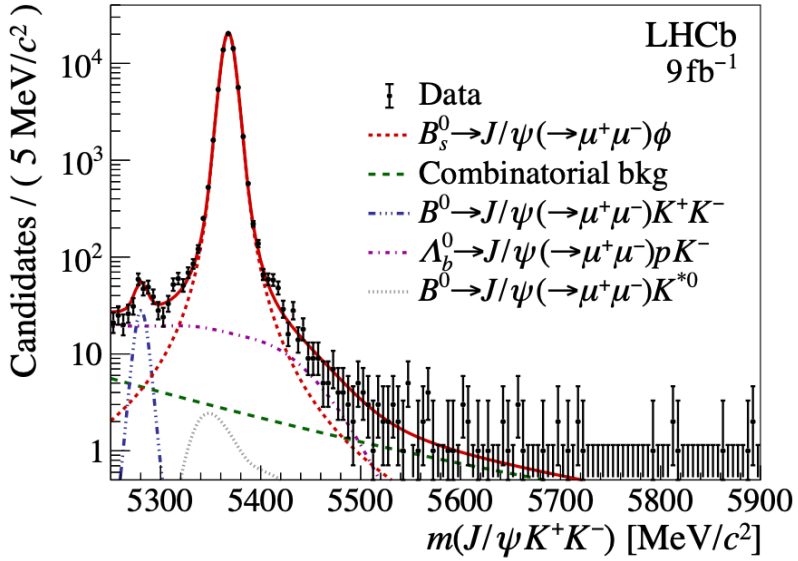
$B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ and $B_s^0 \to \phi\mu^{\pm}e^{\mp}$

arXiv:2207.04005

New | Run1+Run2 dataset

- Tensions with SM observed LFU tests motivate search for **LFV *b*-hadron decays**
- Parallel search for $\boldsymbol{B^0 \to K^{*0}\mu^{\pm}e^{\mp}}$ and $\boldsymbol{B_s^0 \to \phi\mu^{\pm}e^{\mp}}$
- **Analysis strategy**
  - $K^{*0}(892)$ and $\phi(1020)$ reconstructed via $K^{*0} \to K^+\phi^-$ and $\phi \to K^+K^-$
  - Charge split $B^0 \to K^{*0}\mu^{\pm}e^{\mp}$ into $K^+\mu^+$ and $K^+\mu^-$
  - $B^0 \to J/\psi(\mu^+\mu^-)K^{*0}$ and $B_s^0 \to J/\psi(\mu^+\mu^-)\phi$ used as **normalisation channels**
  - **Background rejection**
    - dedicated vetoes to reject background from misID in *b*-hadron decays
    - multivariate classifiers trained against combinatorial background





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

arXiv:2207.04005

New | Run1+Run2 dataset

- No significant signal is observed
- **Improved upper limits** @ 90%(95%) CL

$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 5.7(6.9)\times 10^{-9}$$

$$\mathcal{B}(B^0 \to K^{*0}\mu^+e^-) < 6.8(7.9)\times 10^{-9}$$

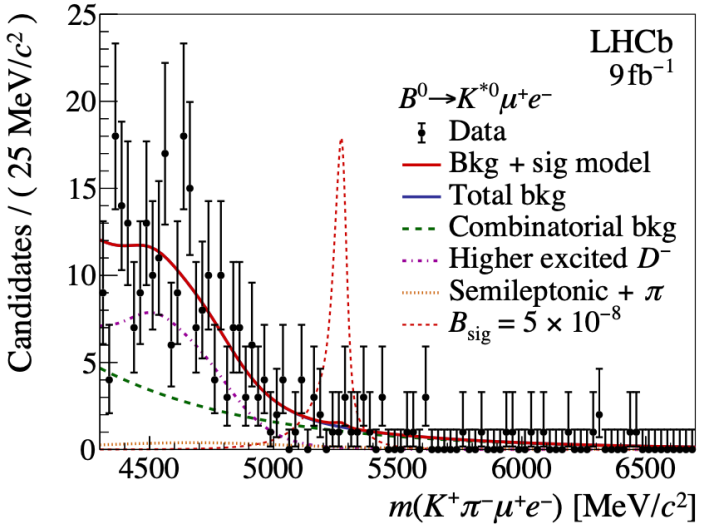
$$\mathcal{B}(B^0 \to K^{*0}\mu^{\pm}e^{\mp}) < 10.1(11.7)\times 10^{-9}$$

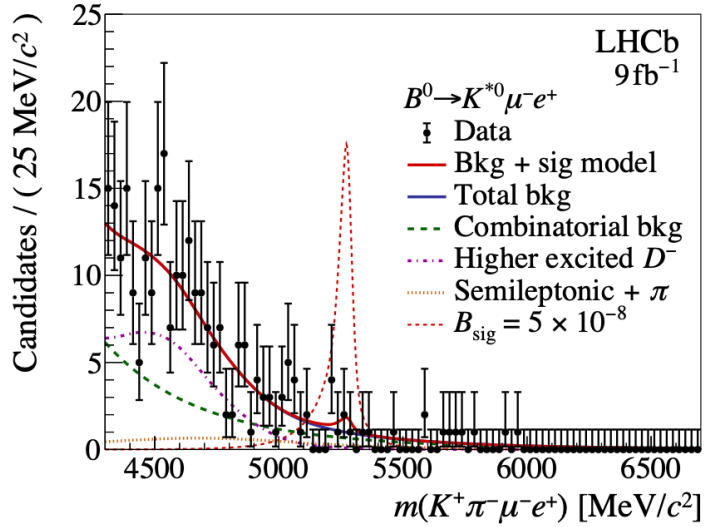
wrt Belle's result (PRD 98, 071101 (2018))

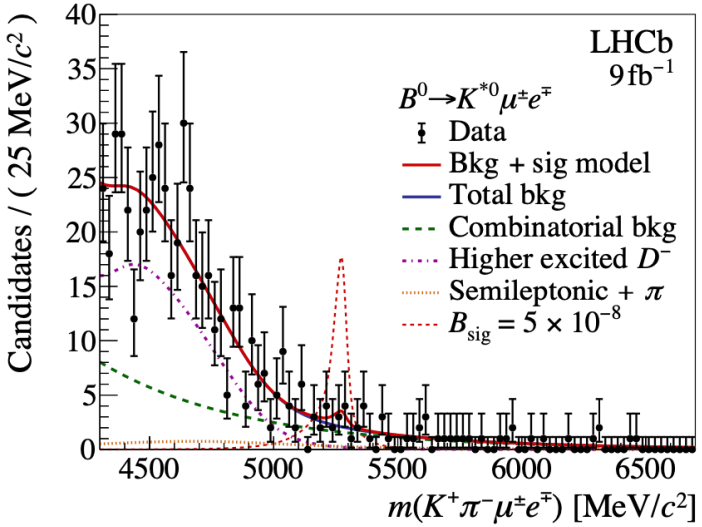
- **World's first limit** set @ 90%(95%) CL

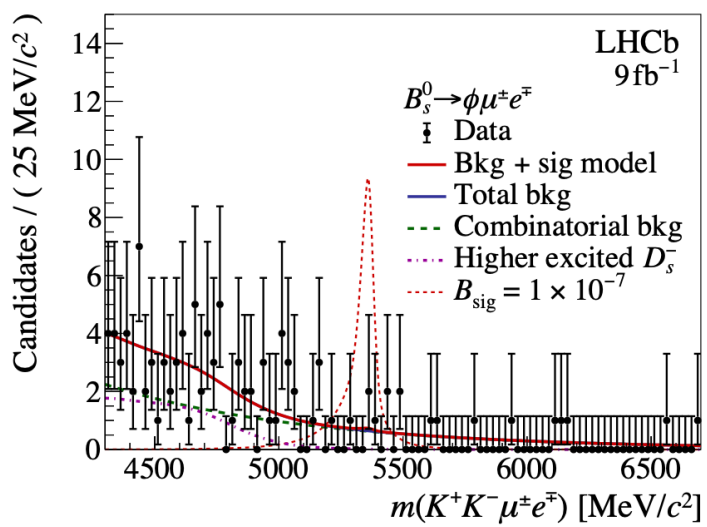
$$\mathcal{B}(B_s^0 \to \phi\mu^{\pm}e^{\mp}) < 16.0(19.8)\times 10^{-9}$$

- Nominal limits assume uniform phase space for signal decays









- (Re-)intepretation in terms of scalar and left-handed LF violating NP models also provided

$\Lambda_b^0 \to \Lambda\gamma$

PRD 105 (2022) L051104

Run2 dataset

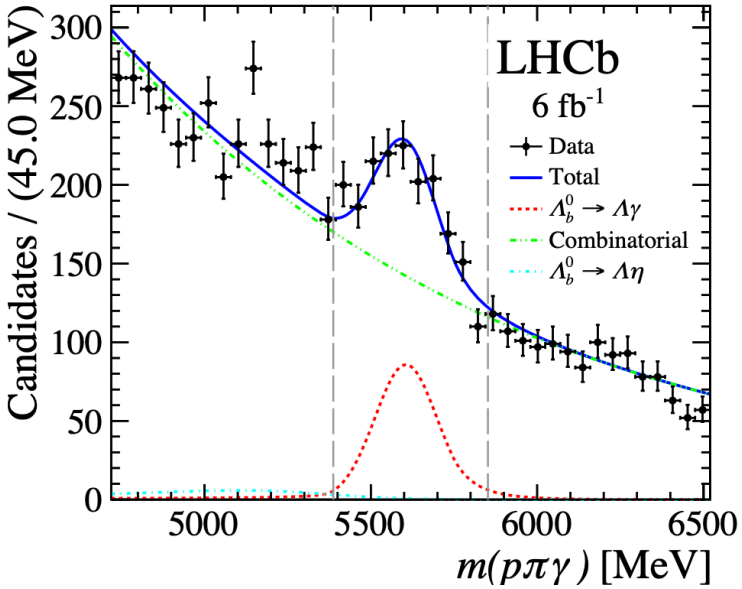
- b-baryons radiative decays allows direct measurement of **photon polarization**
  - due to nonzero spin of the initial- and final-state particles
- First measurement of **photon polarization** in $\Lambda_b^0 \to \Lambda\gamma$ decay, with $\Lambda \to p\pi^-$

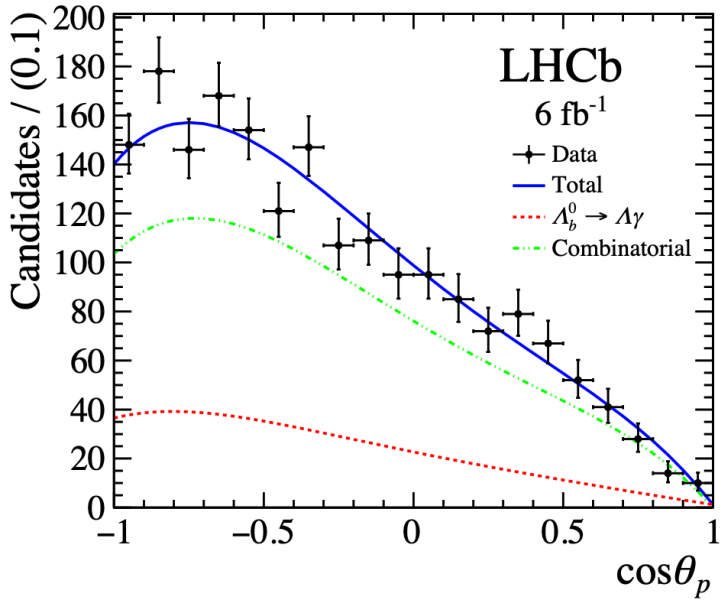
$$\alpha_\gamma \equiv \frac{\gamma_L - \gamma_R}{\gamma_L + \gamma_R}$$

- First study of **CP angular asymmetry** in $b \to s\gamma$ transitions
- **Angular distribution** defined as $\frac{d\Lambda}{d(cos\theta_p)} \sim 1 - \alpha_\gamma \alpha_\Lambda cos\theta_p$ with
  - α_Λ describing interference between parity-violating s-wave and parity-conserving p-wave of $\Lambda \to p\pi^-$ decay
  - θ_p angle between p momentum and negative Λ_b^0 momentum in the Λ rest frame
- Results in agreement with SM predictions and previous measurements in b-meson decays

$$\alpha_\gamma = 0.82^{+0.17\ +0.04}_{-0.26\ -0.13}$$

- **No CP asymmetry** is observed
- Precision of the results dominated by statistical uncertainty





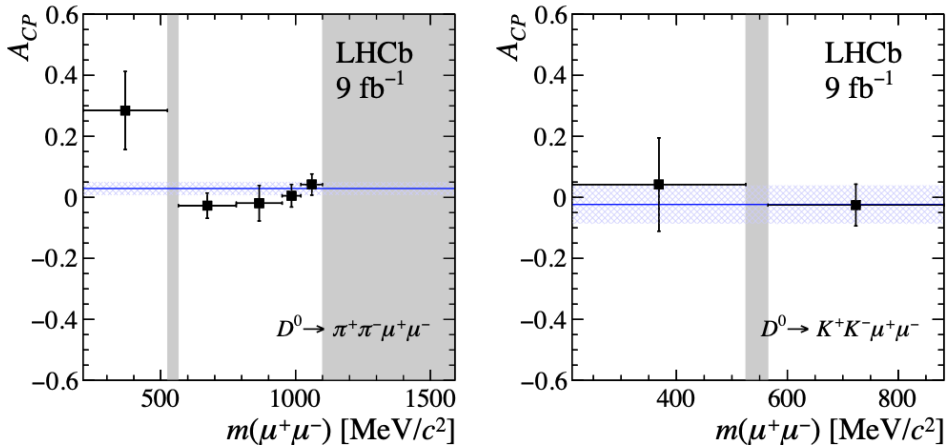
$D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

PRL 128 (2022) 221801

Run1+Run2 dataset

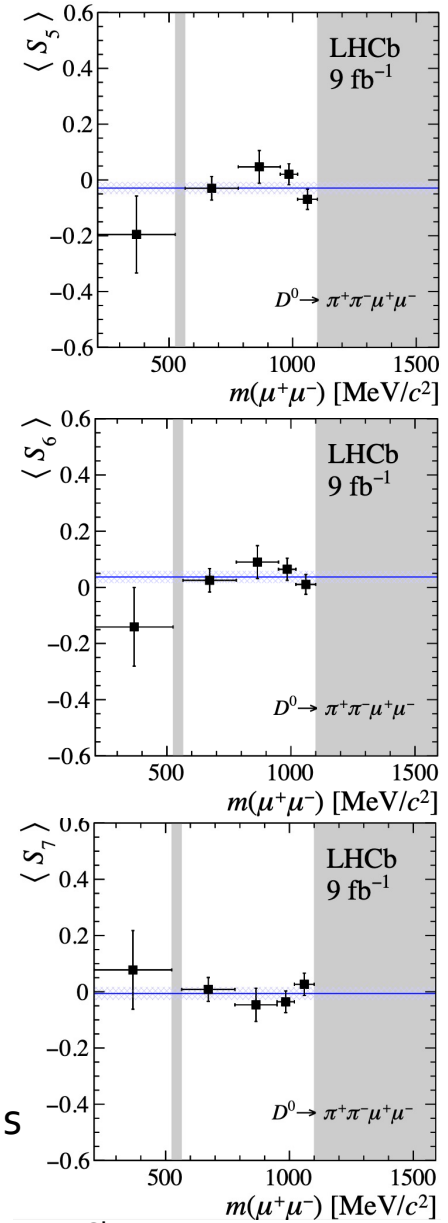
- FCNC $c \to u l^+ l^-$ **transitions** sensitive to BSM contributions
  - More suppressed than $b \to s l^+ l^-$ because of GIM mechanism
  - Long distance effects are dominating
- **First full angular analysis of a rare charm decay**
- Measurement of the full set of CP-averaged angular observables and CP asymmetries as function of $q^2 \equiv m^2(\mu^+\mu^-)$
- **Updated measurement of CP asymmetry**

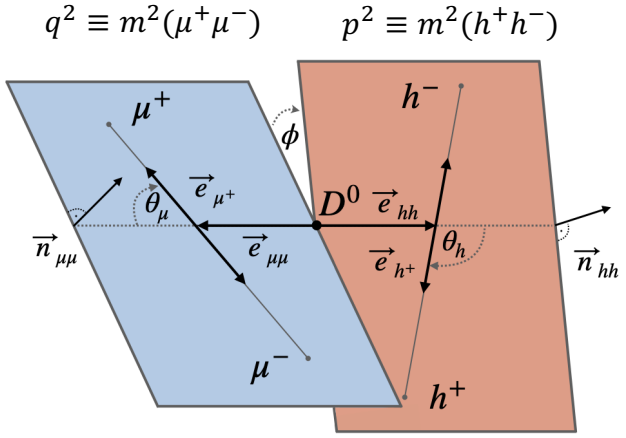
$$A_{CP} \equiv \frac{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) - \Gamma(\bar{D}^0 \to h^+h^-\mu^+\mu^-)}{\Gamma(D^0 \to h^+h^-\mu^+\mu^-) + \Gamma(\bar{D}^0 \to h^+h^-\mu^+\mu^-)}$$

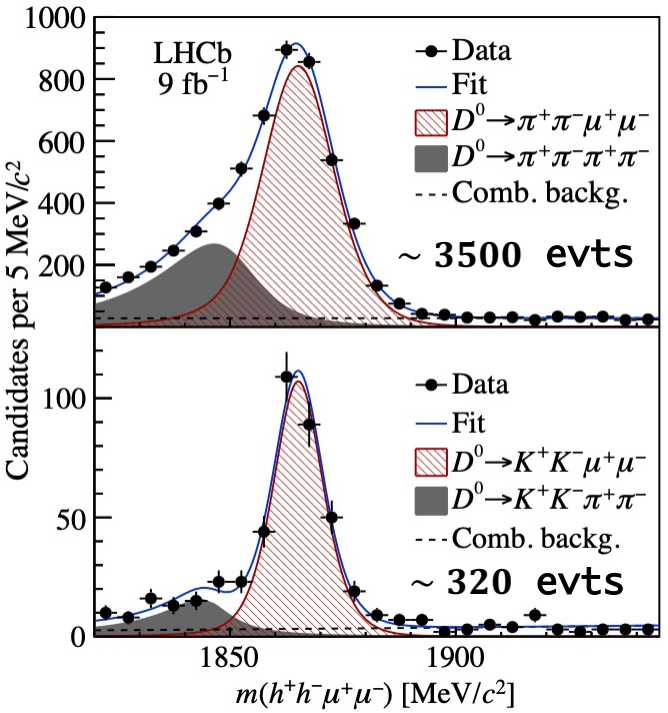


- **Results consistent with SM null hypothesis** with overall *p* values of 79% (0.8%) for $D \to \pi\pi\mu\mu$ ($D \to KK\mu\mu$)

SM null tests







$D^0 \to \mu^+\mu^-$

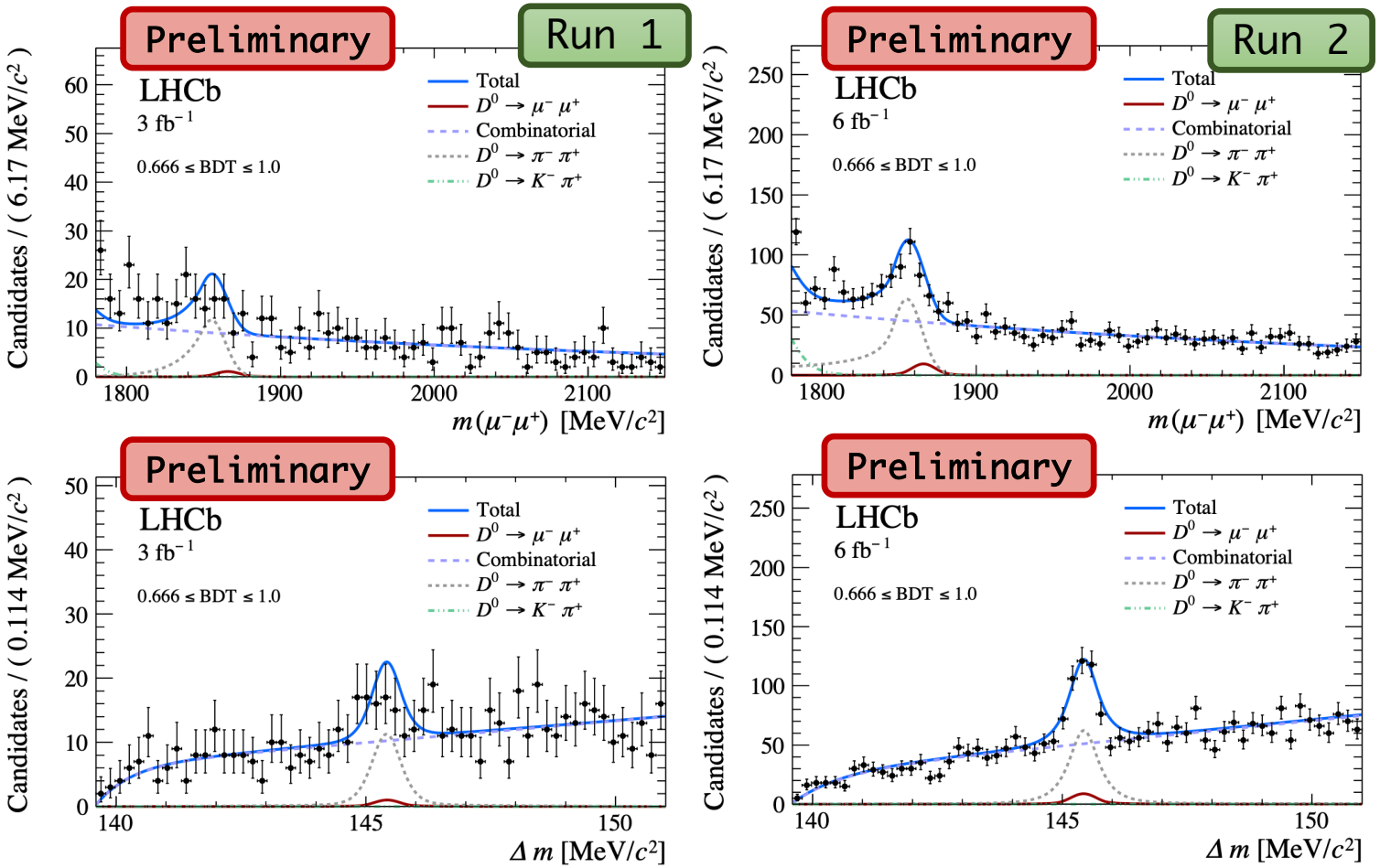
LHCb-PAPER-2022-029 **in preparation**

Run1+Run2 dataset

- SM predicts BF $\sim 10^{-18}$
  - LQ could mediate already at tree level
- Search for $D^0 \to \mu^+\mu^-$ from $D^{*+} \to D^0\pi^+$
  - Improves background rejection
  - 2D fit to $m_{\mu^+\mu^-}$ and $\Delta m = m_{D^{*+}} - m_{D^0}$
- $D^0 \to K^-\pi^+$ and $D^0 \to \pi^+\pi^-$ used as **normalisation channels**
- **Background rejection**
  - Multivariate classifier (BDT) trained against combinatorial
  - PID based classifier to suppress misID background
- **World's most stringent limit**

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.94 \times 10^{-9} \text{ @ } 90\% \text{ CL}$$

Fit in most sensitive BDT bin



More than a factor two improvement wrt previous LHCb result

Summary and conclusions

- Precise measurements of flavour observables represent a powerful way to constrain BSM physics
  - Most results in agreement with SM prediction
  - Though some tensions exist ⟹ motivate further work both in theory and experiments
- LHCb covers a wide range of rare decays
  - A lot more not shown today
  - More analyses with full LHCb dataset will be out soon
- Run 3 data taking has started
  - Upgraded detector and trigger system will enhance signal acceptance
  - 5 times more luminosity for LHCb


Backup