New results in $b \to s\ell^+\ell^-$

SM@LHC 2021

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on behalf of the LHCb collaboration

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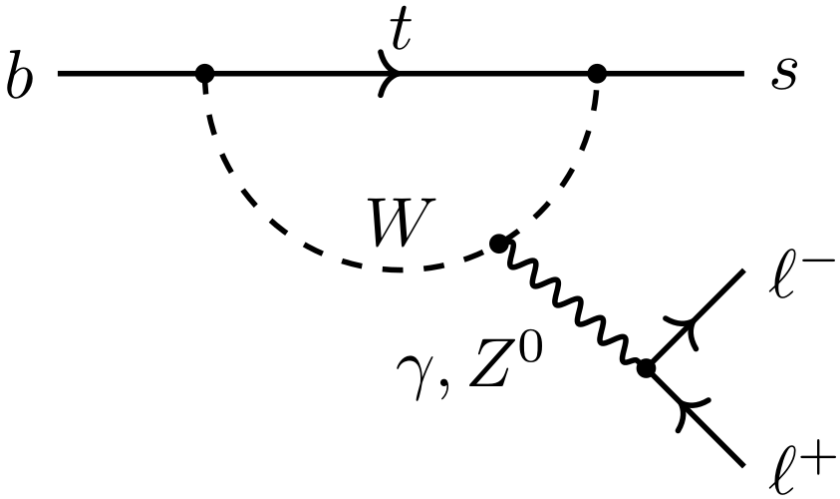
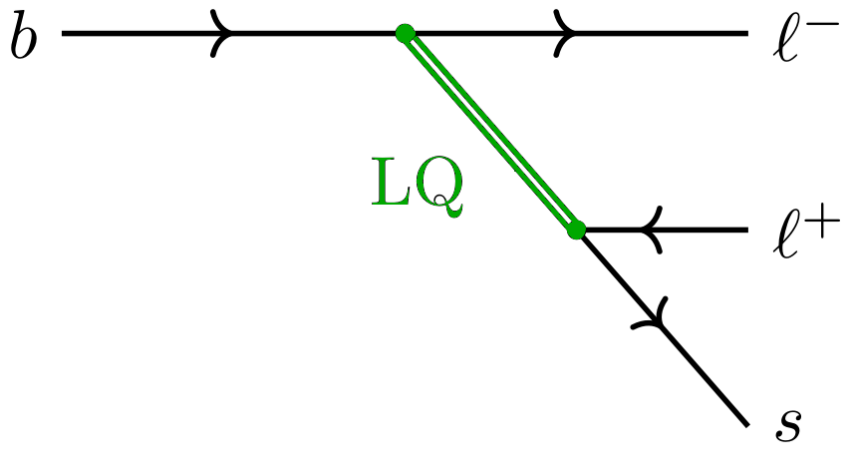
$b \to s\ell^+\ell^-$ transitions

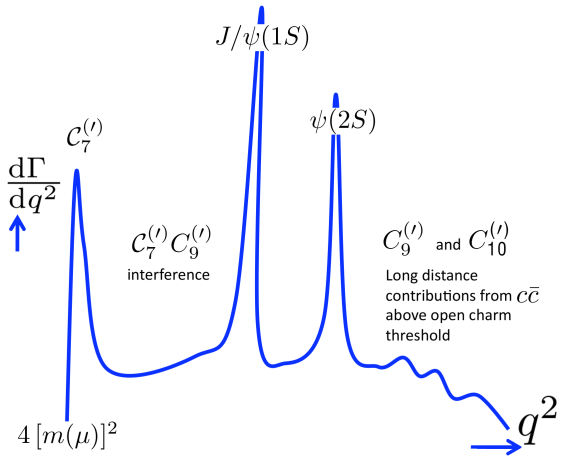




- $b \to s\ell^+\ell^-$ transitions are **flavour-changing neutral-currents**
- Forbidden at tree-level in SM, **loop-suppressed**
- **Sensitive to new heavy particles** that can modify decay rates, angular observables and asymmetries

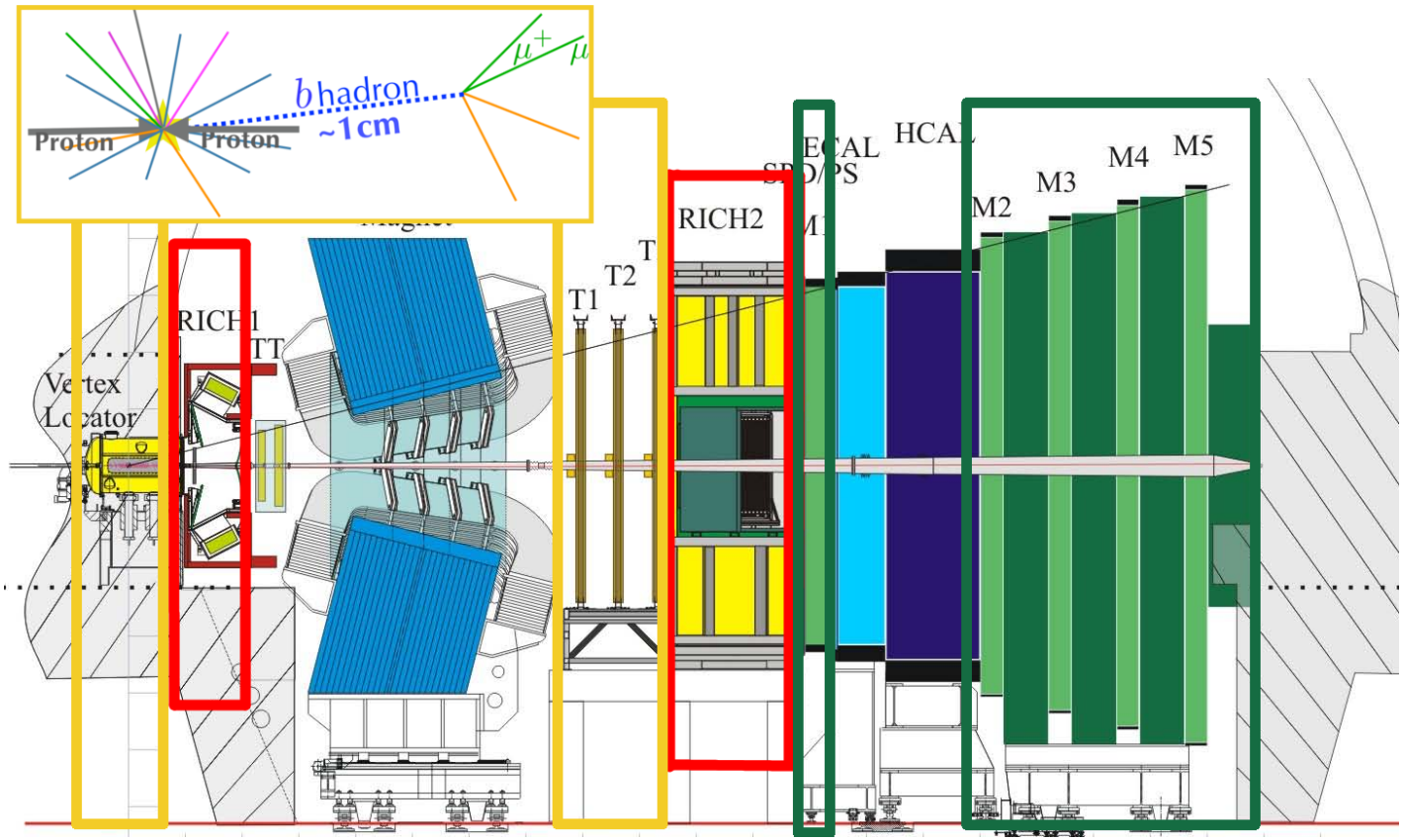
- Measurements as function of $q^2 \equiv m(\ell^+, \ell^-)^2$

$\Rightarrow$ Explore nature of possible new physics



LHCb detector

Tracking (VELO): $\sigma_{IP} = (15 + 29/p_{\mathrm{T}}[\mathrm{GeV}])\mu\ \mathrm{m}$



RICH - Particle ID

Kaon identification: 95%

for around 5% ($\pi \to K$) mis-id probability

Muon system - Muon trigger & ID

Muon identification: around 97 %

for 1-3% ($\pi \to \mu$) mis-id probability

Test of Lepton Flavour Universality R_K (1/3)

Update of R_K with Run 1 and Run 2 data

[arXiv:2103.11769]

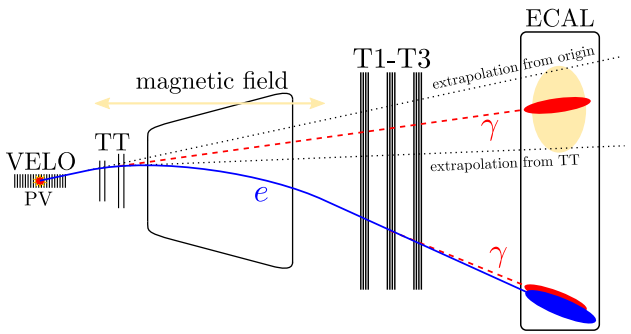
- **Test of Lepton Flavour Universality R_K:**

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} \overset{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-2})$$

Theoretically clean (hadron. uncert. $\mathcal{O}(‰)$, QED $\mathcal{O}(\%)$ [Bordone et al., EPJC 76 (2016) 8:440])

- **Challenge: Measurement of electrons**

Bremsstrahlung: Reduced momentum resolution
ECAL occupancy: Lower trigger rate
$\Rightarrow$ Fewer electrons than muons, with worse resolution



- **Measurement via double-ratio:**

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

$$= \frac{N_{K^+\mu^+\mu^-} / \epsilon_{K^+\mu^+\mu^-}}{N_{K^+(J/\psi \to \mu^+\mu^-)} / \epsilon_{K^+(J/\psi \to \mu^+\mu^-)}} \Big/ \frac{N_{K^+e^+e^-} / \epsilon_{K^+e^+e^-}}{N_{K^+(J/\psi \to e^+e^-)} / \epsilon_{K^+(J/\psi \to e^+e^-)}}$$

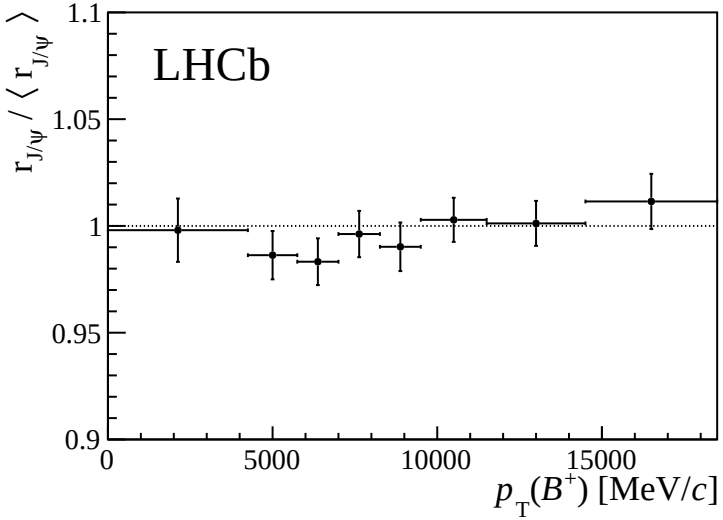
Good control of efficiencies in ratios

Test of Lepton Flavour Universality R_K (2/3)

[arXiv:2103.11769]

- **Powerful validation:**

$$r_{J/\psi} \equiv \frac{\mathcal{B}(B^+ \to K^+(J/\psi \to \mu^+\mu^-))}{\mathcal{B}(B^+ \to K^+(J/\psi \to e^+e^-))} = 1$$

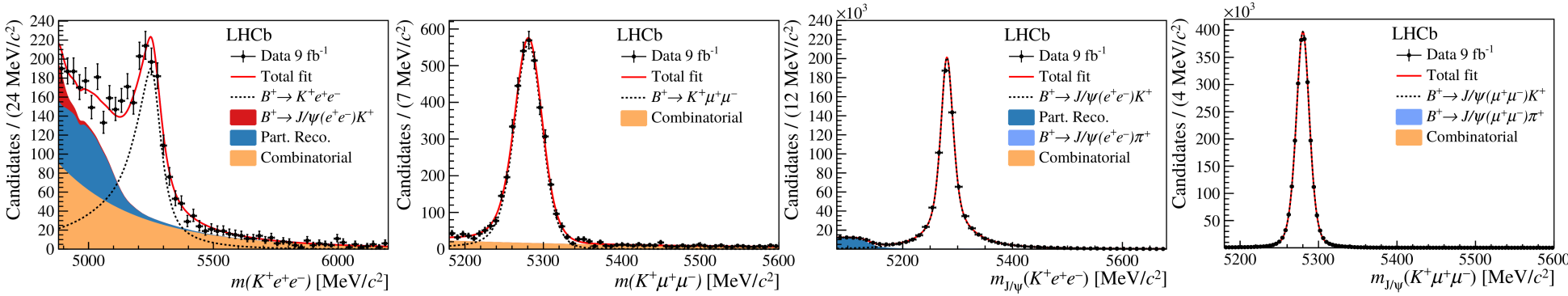


Tested in many variables and regions

Integrated value: $r_{J/\psi} = 0.981 \pm 0.020$ ✓

- **Fits to extract R_K:**

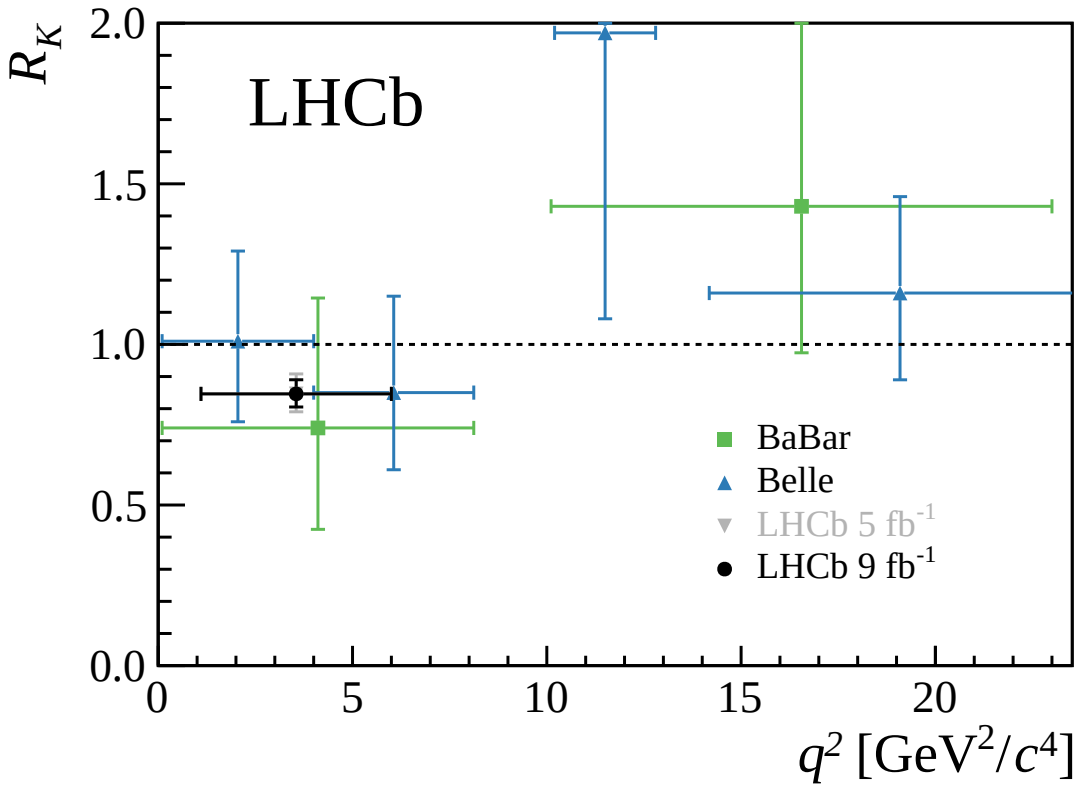
$B^+ \to K^+e^+e^-$ $B^+ \to K^+\mu^+\mu^-$ $B^+ \to K^+(J/\psi \to e^+e^-)$ $B^+ \to K^+(J/\psi \to \mu^+\mu^-)$



[arXiv:2103.11769]

Test of Lepton Flavour Universality R_K (3/3)

R_K using full Run 1 and Run 2 data set: [arXiv:2103.11769]



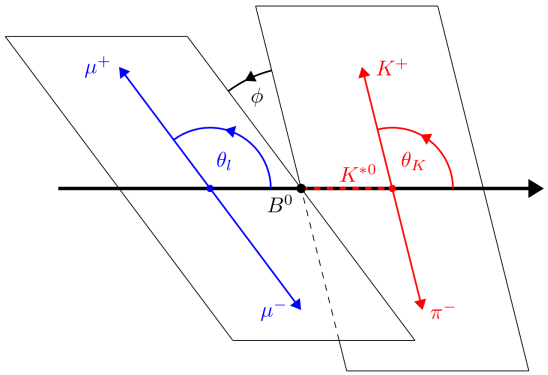
$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846^{+0.043+0.013}_{-0.039-0.012}$$

which is **3.1σ** lower (p-value 0.10%) compared to SM expectation

Angular analyses of $B^+ \to K^{*+}\mu^+\mu^-$ and $B^0 \to K^{*0}\mu^+\mu^-$

Decays can be fully-described by 4-dimensional decay rate:

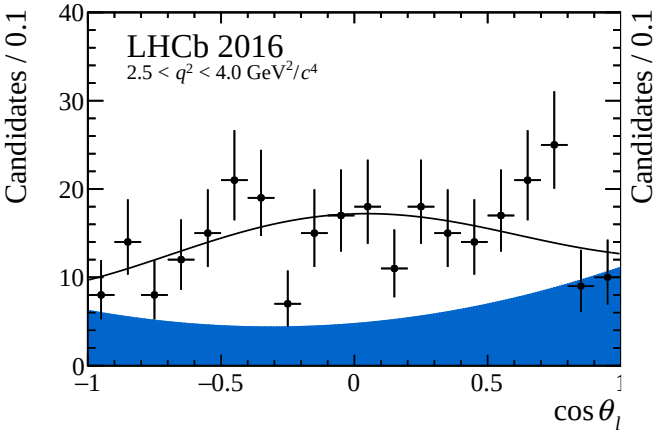
$$\frac{\mathrm{d}^4\Gamma(B \to K^*\mu^+\mu^-)}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega})$$

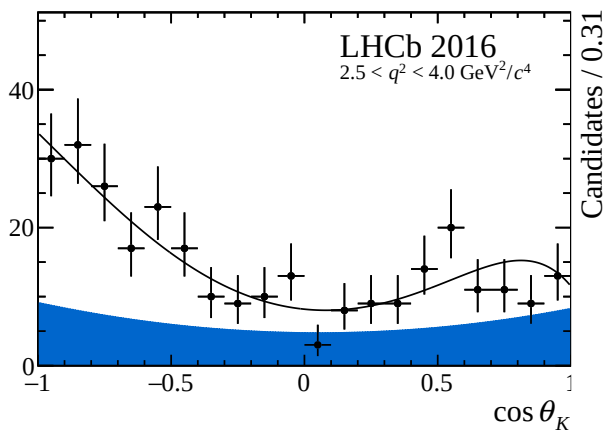


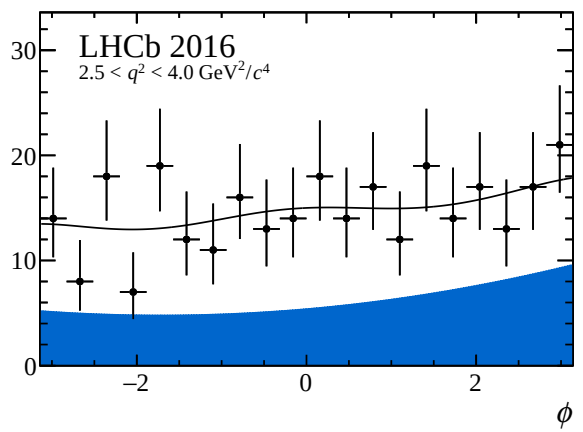
$I_i(q^2)$: angular coefficients
$f_i(\vec{\Omega})$: angular functions

- Averaging over B and $\bar{B}$ decays + q^2-integration: **8 observables**
- Measurement: Extract CP-averaged observables **from fit to data**

e.g. $B^0 \to K^{*0}\mu^+\mu^-$ analysis:







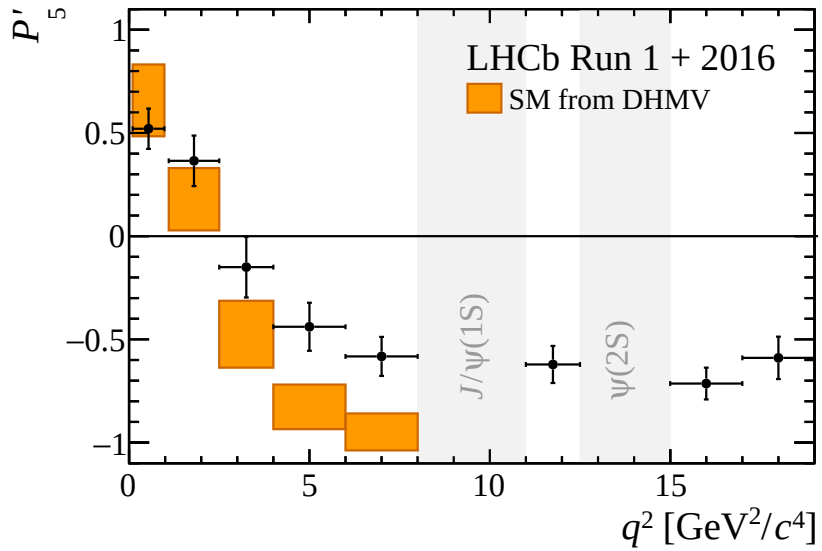
[PRL 125 (2020) 011802]

Angular analyses of $B^+ \to K^{*+}\mu^+\mu^-$ and $B^0 \to K^{*0}\mu^+\mu^-$

$B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 (2020) 011802]

- Update using 2011–2012+2016 data
- Global tension* with SM: **3.3σ**

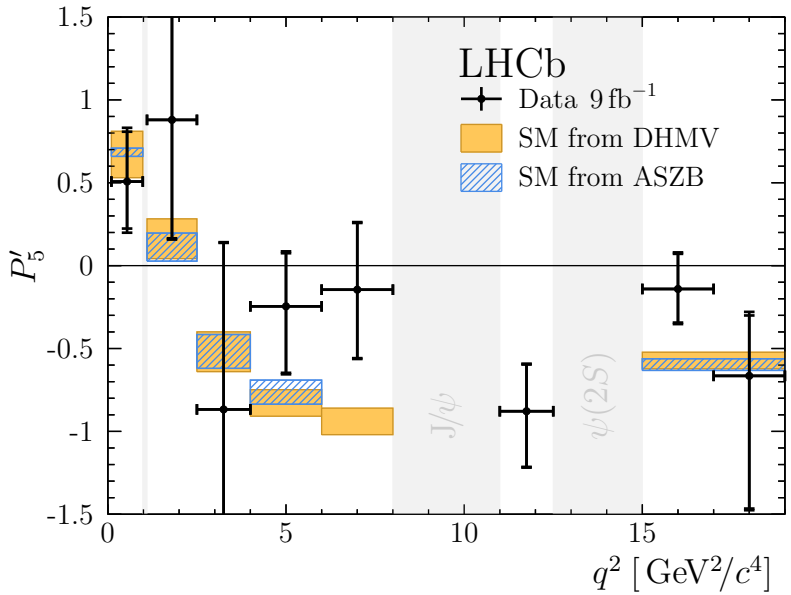
($q^2 \in [0.1, 0.98] \cup [1.1, 8] \cup [15, 19]\,\mathrm{GeV}^2/c^4$)



$B^+ \to K^{*+}\mu^+\mu^-$ [PRL 126 (2021) 161802]

- Using 2011–2018 data
- First time: Full set of observables
- Global tension* with SM: **3.1σ**

($q^2 \in [0.1, 0.98] \cup [1.1, 6] \cup [15, 19]\,\mathrm{GeV}^2/c^4$)



* in underlying effective couplings

$B^0_{(s)} \to \mu^+\mu^-$ (1/3)

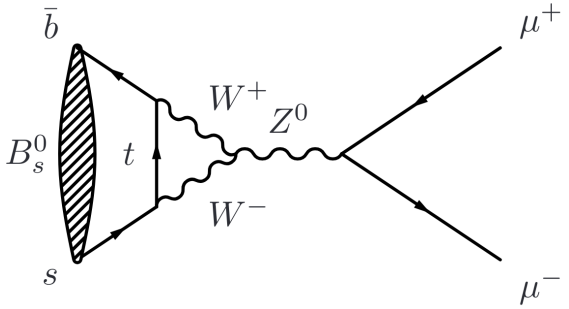
[LHCB-PAPER-2021-007, in preparation]

Improved measurement of $B^0_{(s)} \to \mu^+\mu^-$ decays

- Using Run 1 and Run 2 data set
- Includes search for $B^0_s \to \mu^+\mu^-\gamma$ (with $m_{\mu^+\mu^-} > 4.9\,\mathrm{GeV}/c^2$)

Measurement strategy:

$$\mathcal{B}(B^0_{(s)} \to \mu^+\mu^-) = \frac{\mathcal{B}_{\text{norm.}}\,\epsilon_{\text{norm.}}\,f_{\text{norm.}}}{N_{\text{norm.}}\,\epsilon_{\text{sig.}}\,f_{\text{sig.}}} \times N_{B^0_{(s)} \to \mu^+\mu^-}$$

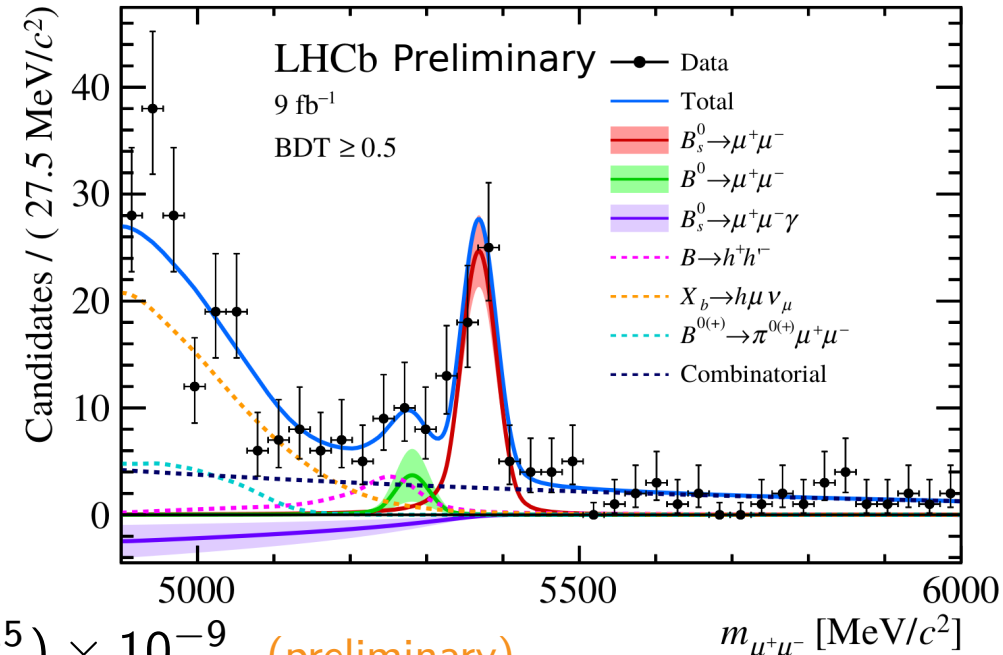


- Measurement relative to **normalisation modes**: $B^+ \to J/\psi\,K^+$ and $B^0 \to K^+\pi^-$
- Yields in data: $N_{B^0_{(s)} \to \mu^+\mu^-}$ and $N_{\text{norm.}}$
- **Efficiencies** ϵ from corrected simulation
- Extract $\mathcal{B}$ from **simultaneous fit to data** in 5 BDT bins

$B^0_{(s)} \to \mu^+\mu^-$ (2/3)

[LHCB-PAPER-2021-007, in preparation]

- $B^0_s \to \mu^+\mu^-$ re-observed (10σ)
- $B^0 \to \mu^+\mu^-$ not observed (1.7σ)
- $B^0_s \to \mu^+\mu^-\gamma$ not observed



$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.09^{+0.46\,+0.15}_{-0.45\,-0.11}) \times 10^{-9}$$ (preliminary)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$ [Beneke et al., JHEP 10 (2019) 232]

- Branching fractions at @ 95%CL (preliminary):

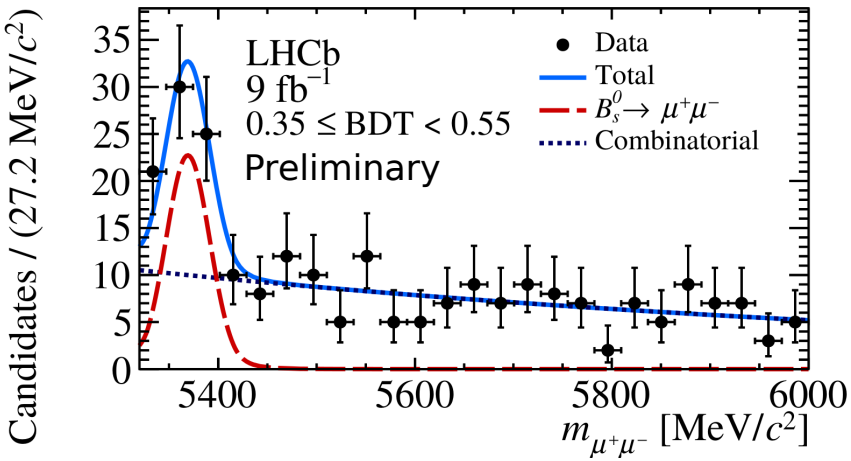
$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$$

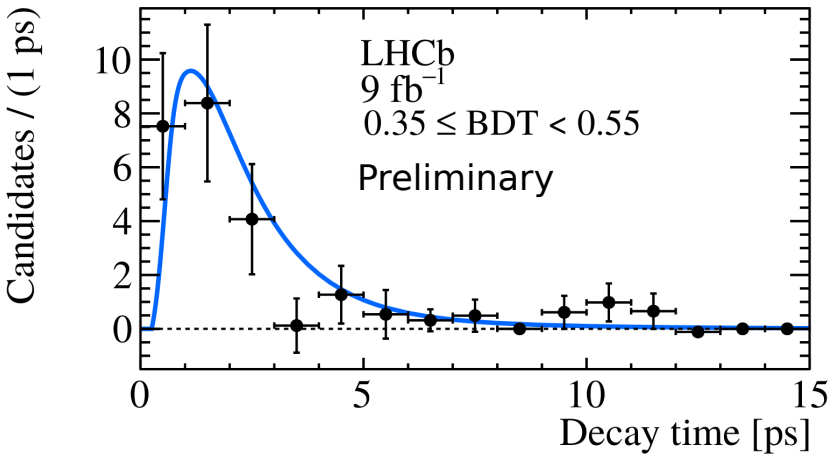
$$\mathcal{B}(B^0_s \to \mu^+\mu^-\gamma) < 2.0 \times 10^{-9} \; (m_{\mu^+\mu^-} > 4.9\,\mathrm{GeV}/c^2)$$

All $\mathcal{B}$ in agreement with SM

$B^0_{(s)} \to \mu^+\mu^-$ (3/3)

[LHCB-PAPER-2021-007, in preparation]





Measurement of $\tau(B^0_s \to \mu^+\mu^-)$

- Test for possible NP contributions from light B^0_s eigenstate ($\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s} = -1$)
- Fit dimuon mass to statistically subtract background

$$\tau(B^0_s \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03\,\text{ps} \quad \text{(preliminary)}$$

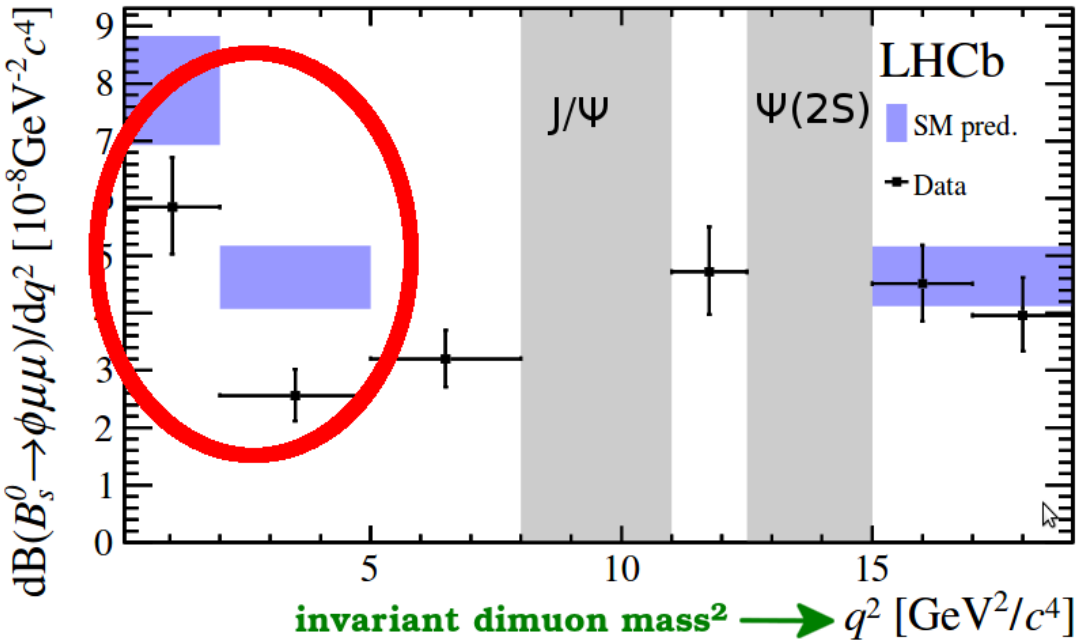
- Compatible with $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s} = 1$ (SM) at 1.5σ and $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s} = -1$ at 2.2σ (preliminary)

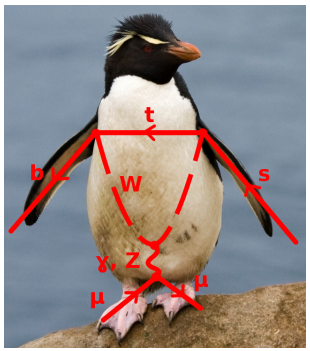
In agreement with the SM expectation

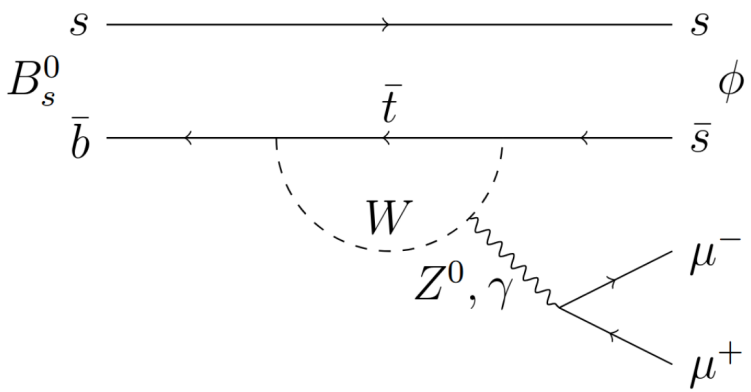
$\mathcal{B}\left(B_s^0 \to \phi\mu^+\mu^-\right)$

Run 1-only analysis:

[JHEP 09 (2015) 179]







- Run 1 result: $\mathcal{B}\left(B_s^0 \to \phi\mu^+\mu^-\right) \sim 3\,\sigma$ lower wrt SM expectation at low q^2

Today: Presenting update using full Run 1 and 2 data set

$\mathcal{B}\,(B_s^0 \to \phi\mu^+\mu^-)$: Measurement strategy

[LHCB-PAPER-2021-014, in preparation]

Measurement strategy:

$$\frac{d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{\mathcal{B}(B_s^0 \to J/\psi\,\phi)dq^2} = \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{q^2_{\text{max}} - q^2_{\text{min}}} \cdot \frac{N_{\phi\mu^+\mu^-}}{N_{J/\psi\phi}} \cdot \frac{\epsilon^{J/\psi\phi}_{\text{tot}}}{\epsilon^{\phi\mu^+\mu^-}_{\text{tot}}}$$

- Relative to control channel with $q^2 \in [8, 11]\,\text{GeV}^2/c^4$
- Event selection (incl. MVA) to reduce backgrounds
- Fits for event yields
- Efficiencies from corrected simulations

$B_s^0 \to \phi\mu^+\mu^-$ data and selection

Data:

- Full data set: (2011–2018)

Offline selection:

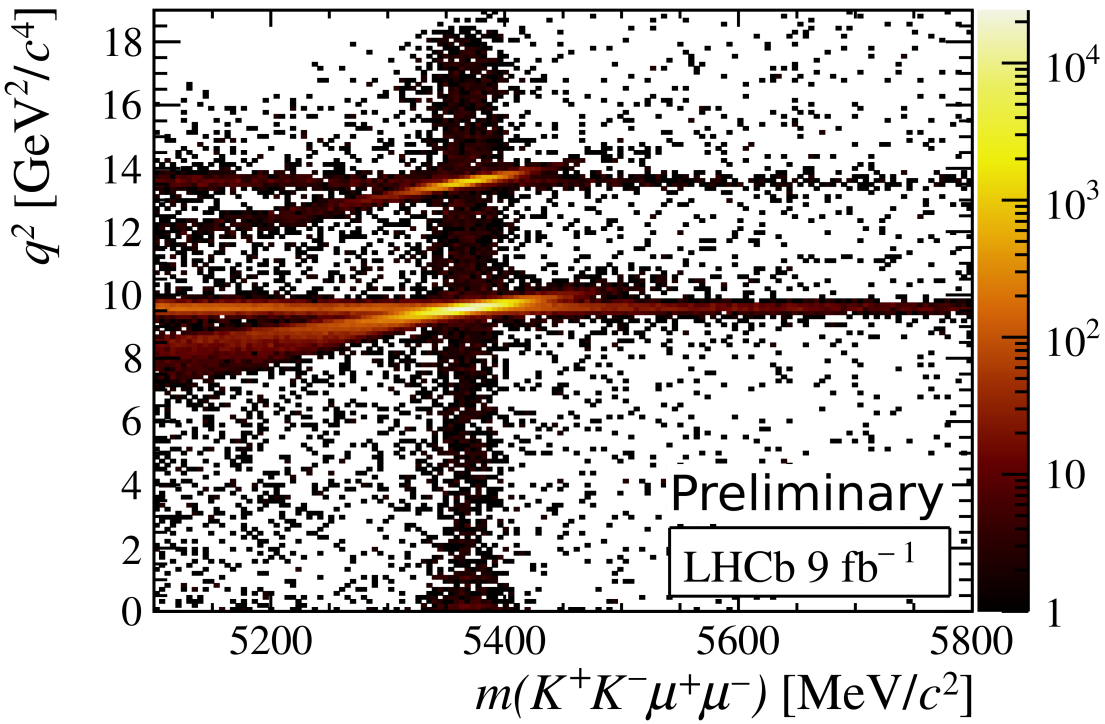
- B_s^0 meson from pp-collision
- flight distance of B_s^0
- kaons, muons well identified
- $|m_{K^+K^-} - m_\phi| < 12.\,\mathrm{MeV}/c^2$

Multivariate classifier:

- trained on data:
  $B_s^0 \to J/\psi\,\phi$ (signal proxy),
  high mass (bkg. proxy)
- variables:
  event topology and PID

Combined data after full selection:

[LHCB-PAPER-2021-014, in preparation]



Signal clearly visible!

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

Mass model:

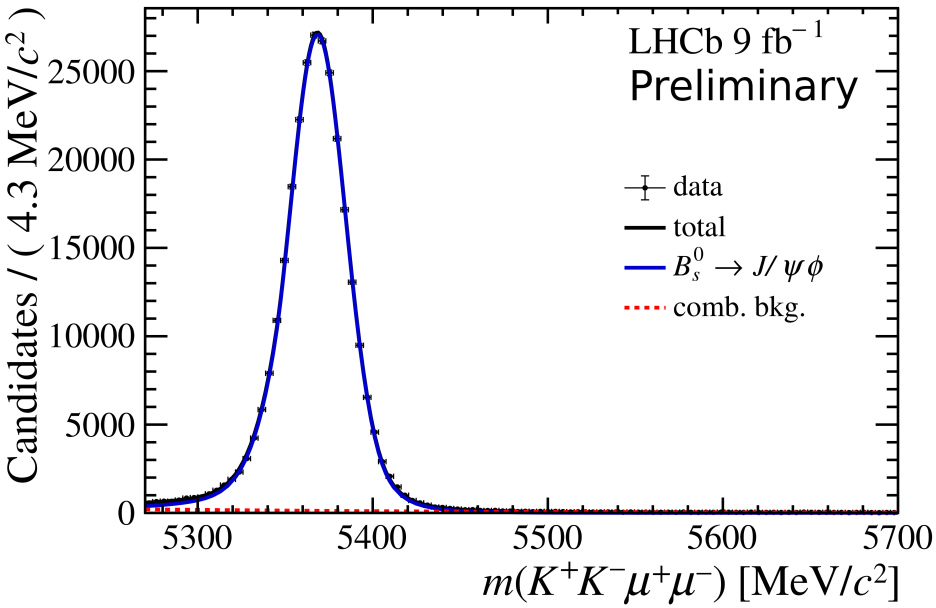
[LHCB-PAPER-2021-014, in preparation]

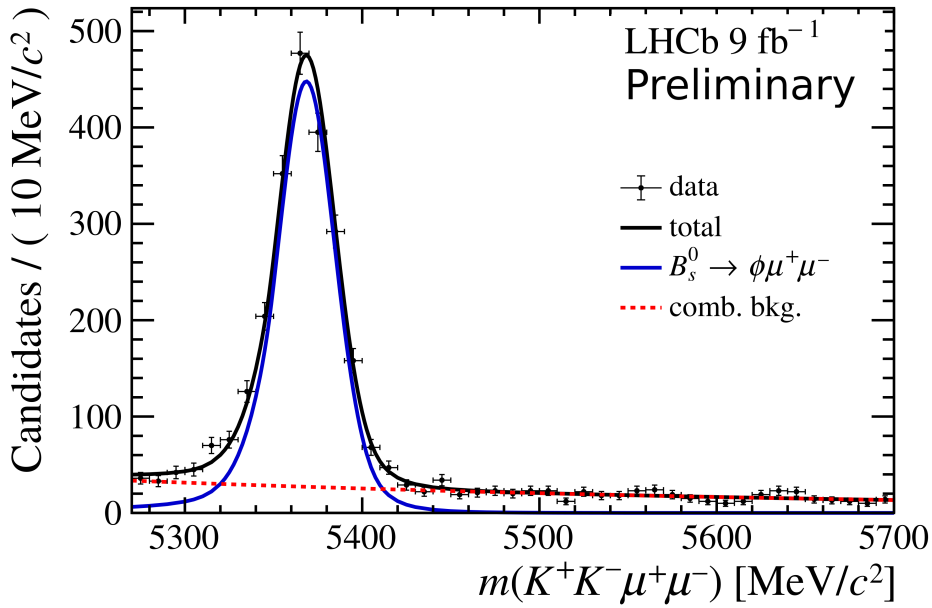
Double Crystal Ball (DCB) for signal

exponential for combinatorial background

$B_s^0 \to J/\psi\,\phi$ $q^2 \in [8, 11]\,\mathrm{GeV}^2/c^4$

$B_s^0 \to \phi\mu^+\mu^-$ $q^2 \in [0.1, 19]\,\mathrm{GeV}^2/c^4$, $q^2 \not\approx m_\phi^2, m_{J/\psi}^2, m_{\psi(2S)}^2$



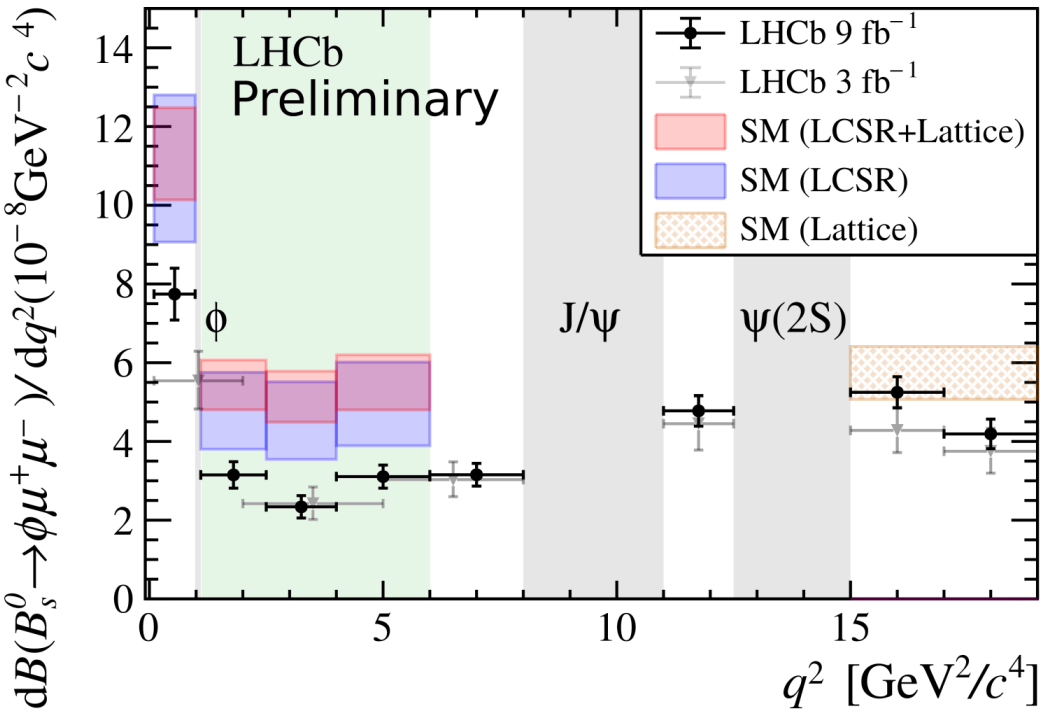


$N(B_s^0 \to J/\psi\,\phi) = 282\,400 \pm 570$ (preliminary)

$N(B_s^0 \to \phi\mu^+\mu^-) = 2006 \pm 53$ (preliminary)

$\mathcal{B}\left(B_s^0 \to \phi\mu^+\mu^-\right)$ result

[LHCB-PAPER-2021-014, in preparation]



Run 1 result:

[JHEP 09 (2015) 179], [arXiv:2103.06810]

SM LCSR:

[Bharucha et al., JHEP 08 (2016) 098],

[Altmannshofer et al., EPJ C 75 (2015) 382],

[Straub, arXiv:1810.08132]

SM LCSR+Lattice:

+[Horgan et al., PRL 112 (2014) 212003],

+[Horgan et al., PoS LATTICE2014 (2015) 372]

$q^2 \in [1.1, 6.0]$ $\mathrm{d}\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)/\mathrm{d}q^2 = (2.88 \pm 0.21) \times 10^{-8}\,\mathrm{GeV}^2/c^4$ (preliminary)

Tension with SM at **1.8σ (LCSR)** and **3.6σ (LCSR+Lattice)**

q^2-integrated $\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (8.14 \underbrace{\pm 0.21}_{\text{stat.}} \underbrace{\pm 0.16}_{\text{syst.}} \underbrace{\pm 0.39}_{\text{norm.}} \underbrace{\pm 0.03}_{q^2\text{ extrap.}}) \times 10^{-7}$ (preliminary)

[JHEP 09 (2015) 179], [arXiv:2103.06810] $\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-) = (7.54^{+0.43}_{-0.41} \pm 0.21 \pm 0.36 \pm 0.22) \times 10^{-7}$

$B_s^0 \to f_2'(1525)\mu^+\mu^-$ strategy

NEW!

First measurement of $B_s^0 \to f_2'(1525)\mu^+\mu^-$

Keep $B_s^0 \to f_2'(1525)\mu^+\mu^-$ analysis as close to $B_s^0 \to \phi\mu^+\mu^-$ as possible

- Measure BF relative to $B_s^0 \to J/\psi\,\phi$
- MVA from $B_s^0 \to \phi\mu^+\mu^-$ analysis
- Sim. corrections from $B_s^0 \to \phi\mu^+\mu^-$ ana.

$\Gamma_{f_2'(1525)} > \Gamma_\phi$: Select larger m_{KK} range

$\Rightarrow$ More backgrounds

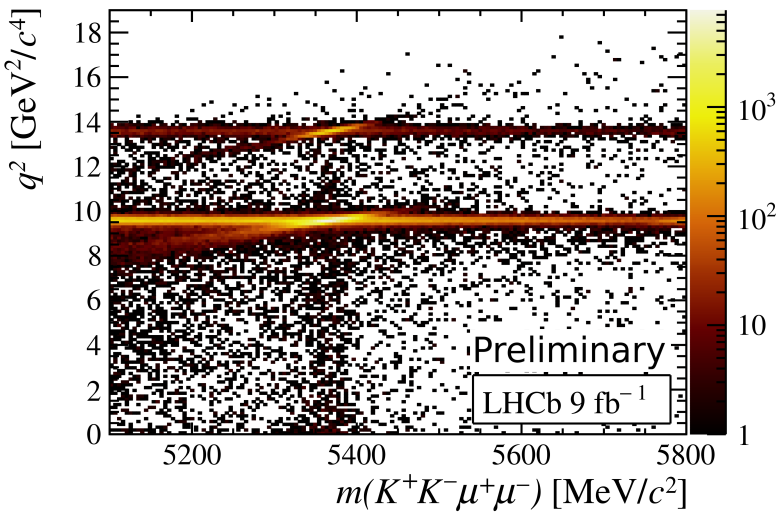
$\Rightarrow$ Need tighter selection

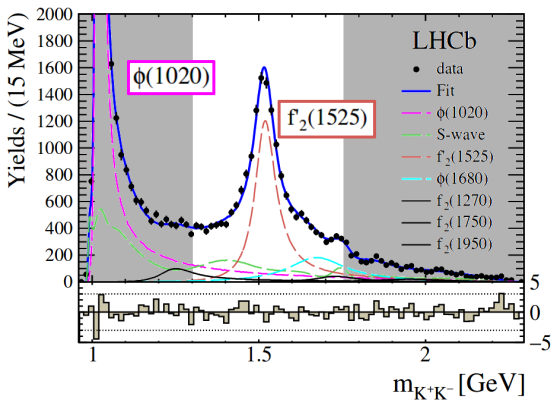
Fit in $m(K^+K^-\mu^+\mu^-)$ and $m(K^+K^-)$

- Separate signal and $B_s^0 \to K^+K^-\mu^+\mu^-$ bkg.
- $B_s^0 \to J/\psi\, f_2'(1525)$ for fit model and checks

Measure in single bin: $q^2 \in [0.1, 15.0]\,\mathrm{GeV}^2/c^4$

[LHCB-PAPER-2021-014, in prep.]

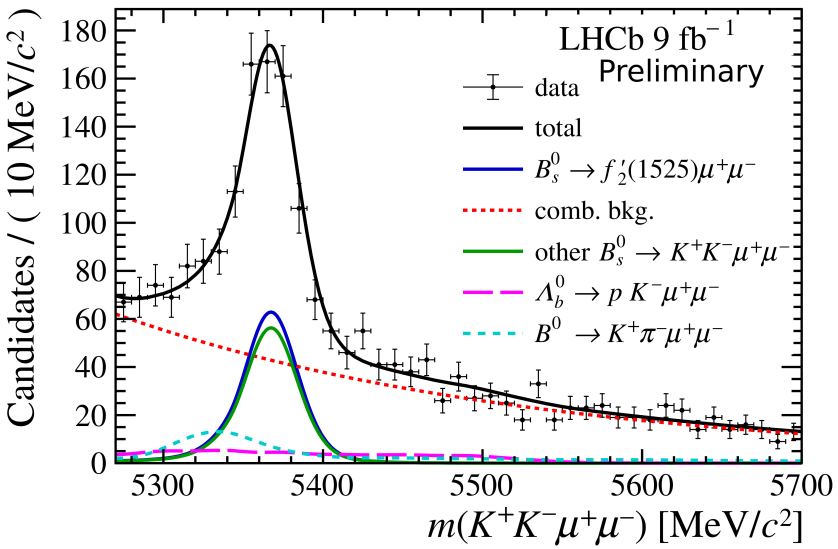


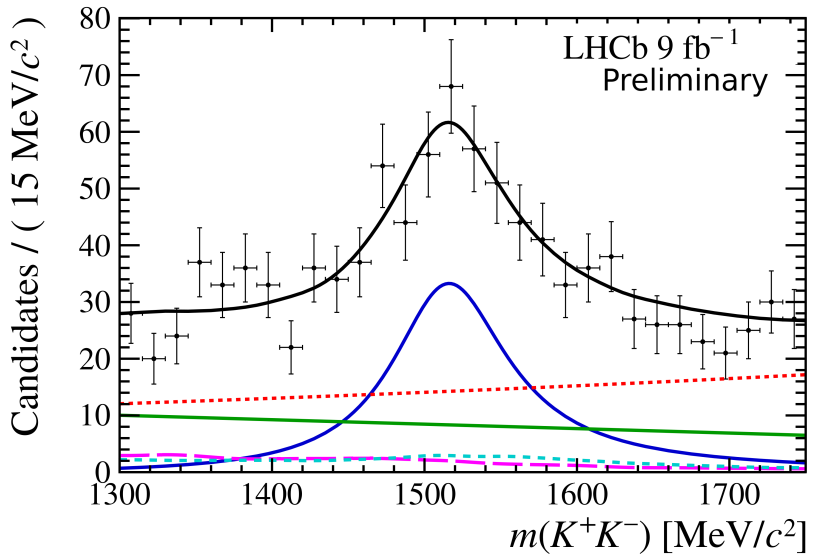


[JHEP 08 (2017) 037]

$B_s^0 \to f_2'(1525)\mu^+\mu^-$ result

[LHCB-PAPER-2021-014, in preparation]





- Observation with $9\,\sigma$ significance ✓ (preliminary)

$$\mathcal{B}(B_s^0 \to f_2'(1525)\mu^+\mu^-) = (1.57 \underbrace{\pm 0.19}_{\text{stat.}} \underbrace{\pm 0.06}_{\text{syst.}} \underbrace{\pm 0.06}_{q^2 \text{ extrap.}} \underbrace{\pm 0.08}_{\text{norm.}}) \times 10^{-7} \quad \text{(preliminary)}$$

In agreement with SM predictions

Conclusions

Presented results from LHCb $b \to s\ell^+\ell^-$ measurements:

- Test of Lepton Flavour Universality R_K
- Angular analyses of $B^0 \to K^{*0}\mu^+\mu^-$ and $B^+ \to K^{*+}\mu^+\mu^-$
- Updated measurement of $B^0_{(s)} \to \mu^+\mu^-$ decays

Presented for the first time:

- Update of $\mathcal{B}(B^0_s \to \phi\mu^+\mu^-)$ using the full Run 1+Run 2 LHCb data set
  Tension with SM predictions in $q^2 \in [1.1, 6.0]\,\mathrm{GeV}^2/c^4$:
  $1.8\,\sigma$ (LCSR) and **$3.6\,\sigma$** (LCSR+Lattice) (preliminary)
- Observation of $B^0_s \to f_2'(1525)\mu^+\mu^-$
  $\mathcal{B}(B^0_s \to f_2'(1525)\mu^+\mu^-)$ compatible with SM predictions

Interesting tensions across $b \to s\ell^+\ell^-$ observables.
More data needed to confirm these trends!

Outlook: Other updates expected soon

- Update of $B^0_s \to \phi\mu^+\mu^-$ angular
- Update of $B^0 \to K^{*0}\mu^+\mu^-$ using full data set
- R_{K^*}, R_ϕ
- ...