Flavour physics with rare, electroweak-penguin, and semileptonic decays at LHCb

Zhenzi Wang
on behalf of the LHCb collaboration

University of Zurich

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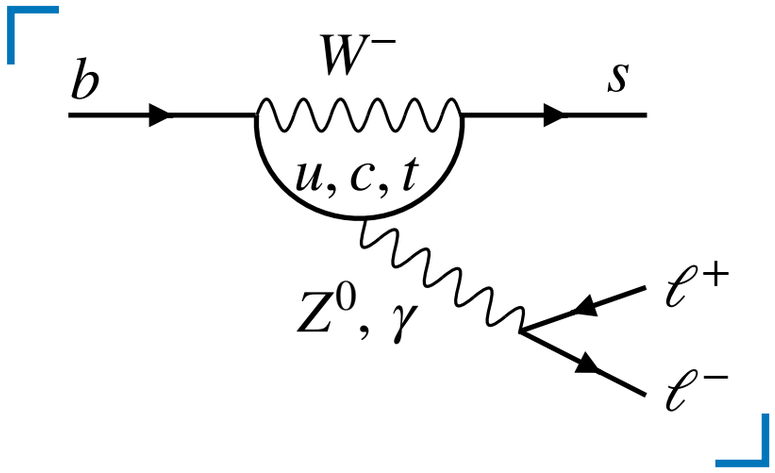
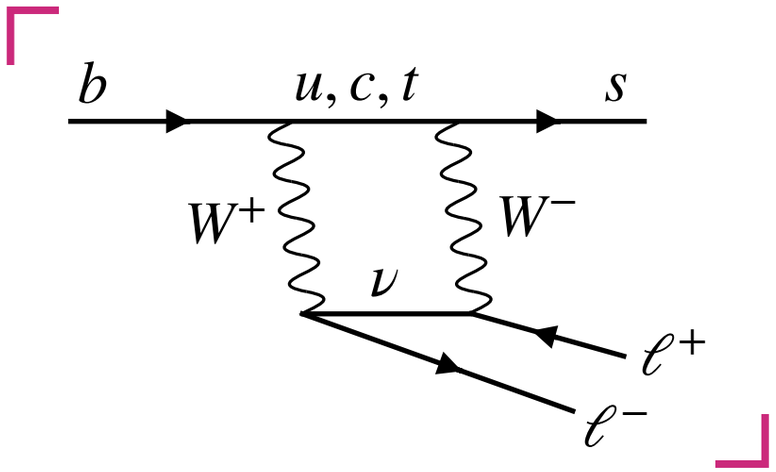
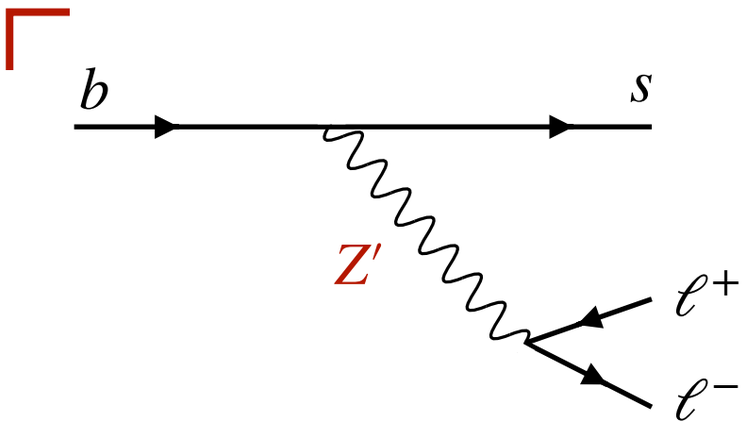
Rare decays

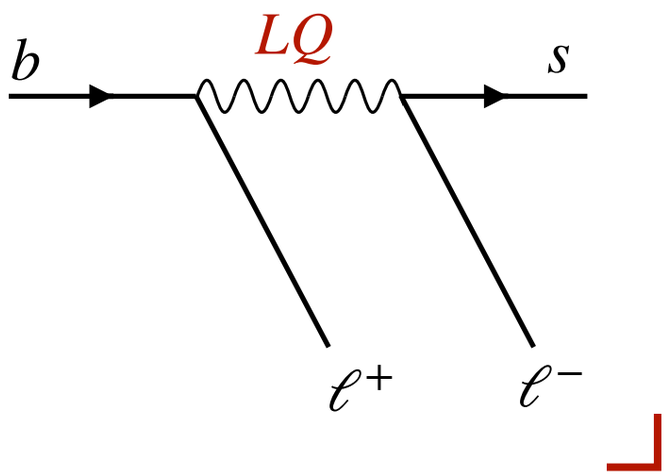
- Rare decays of b-hadrons are flavour changing neutral current (FCNC) decays that only occur at loop level in the SM via ‘penguin’ and ‘box’ type diagrams





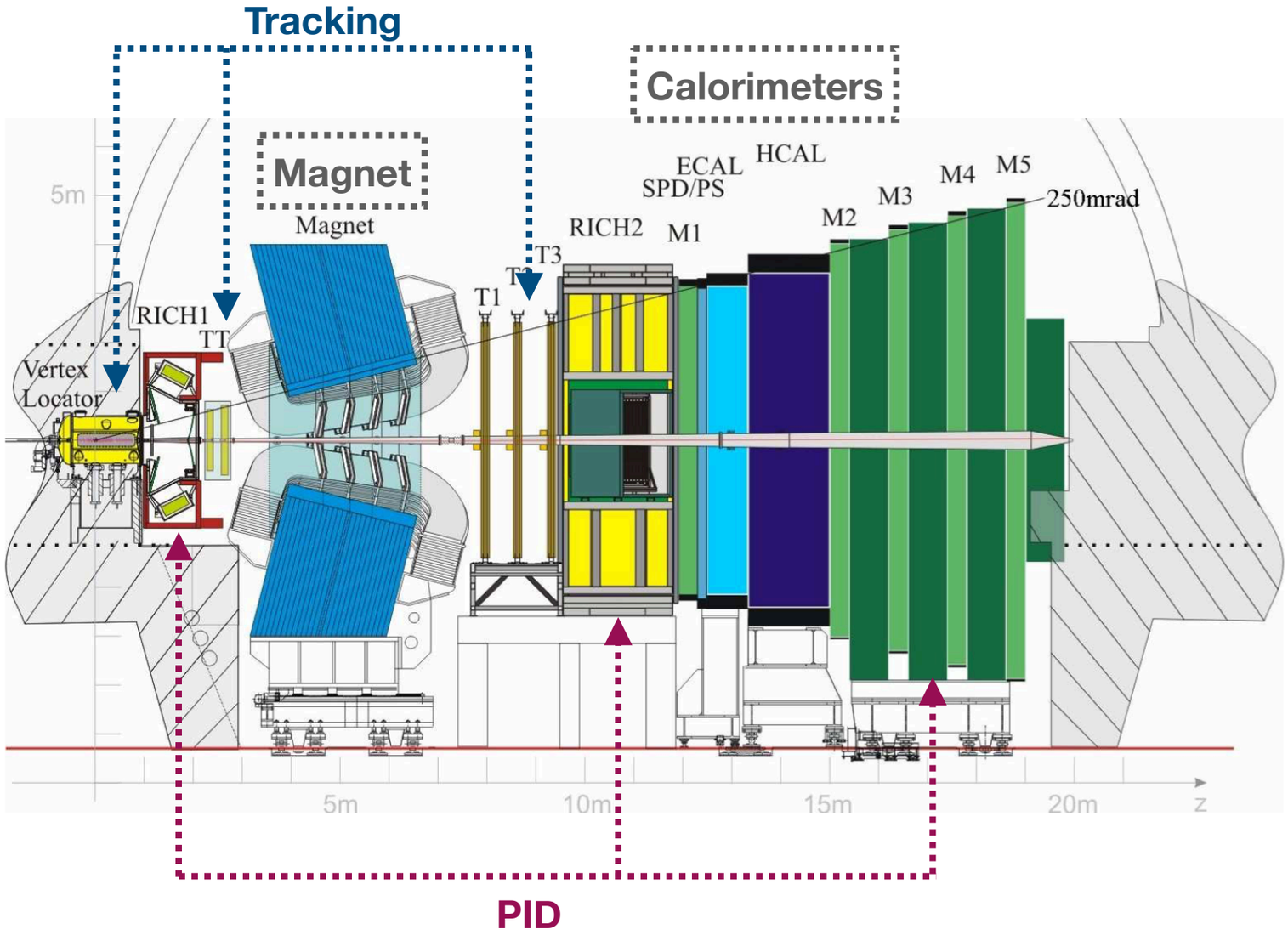
- Low SM background — excellent for indirect searches of non-SM contributions

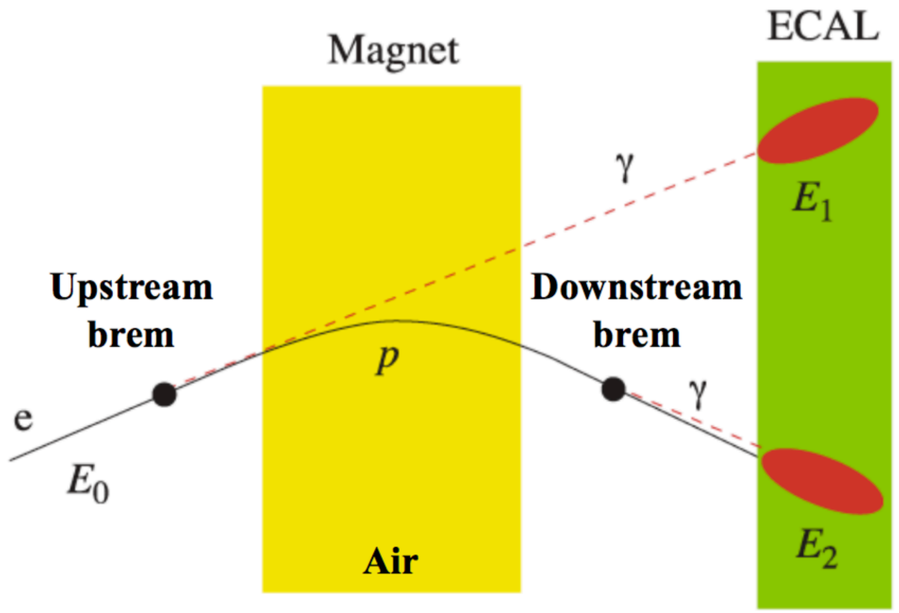




The detector

- The LHCb detector is optimised for the study of b-hadron decays





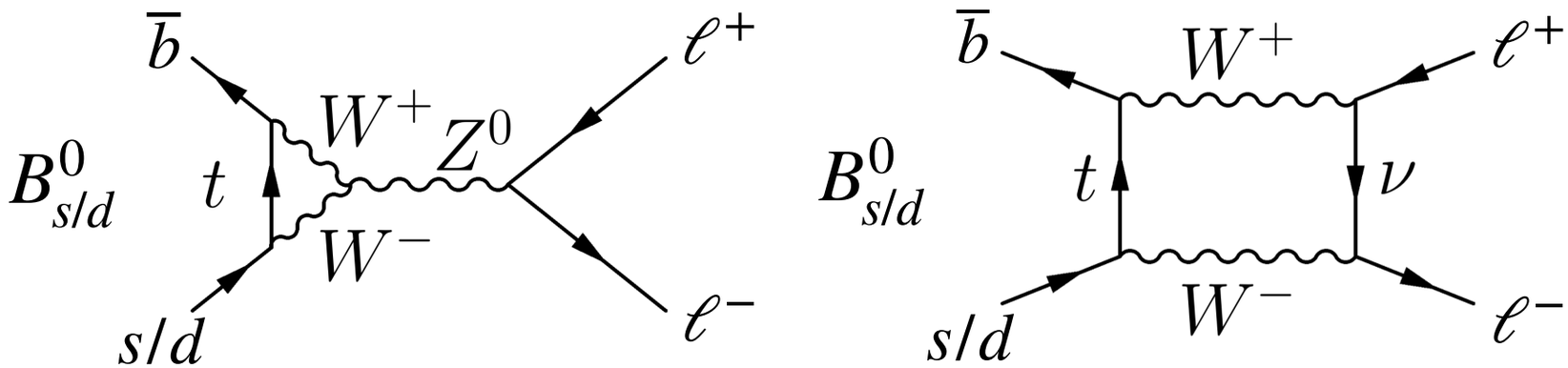
- Electron reconstruction presents challenges

  => partially compensated by bremsstrahlung recovery algorithm

- Detector upgrade is underway — planned to restart in 2022 (pre-upgrade detector illustrated)

Rare decays — $B^0_{(s)} \to \ell^+\ell^-$

- $B^0_{(s)} \to \ell^+\ell^-, \ell = e, \mu, \tau$ are helicity suppressed FCNC decays

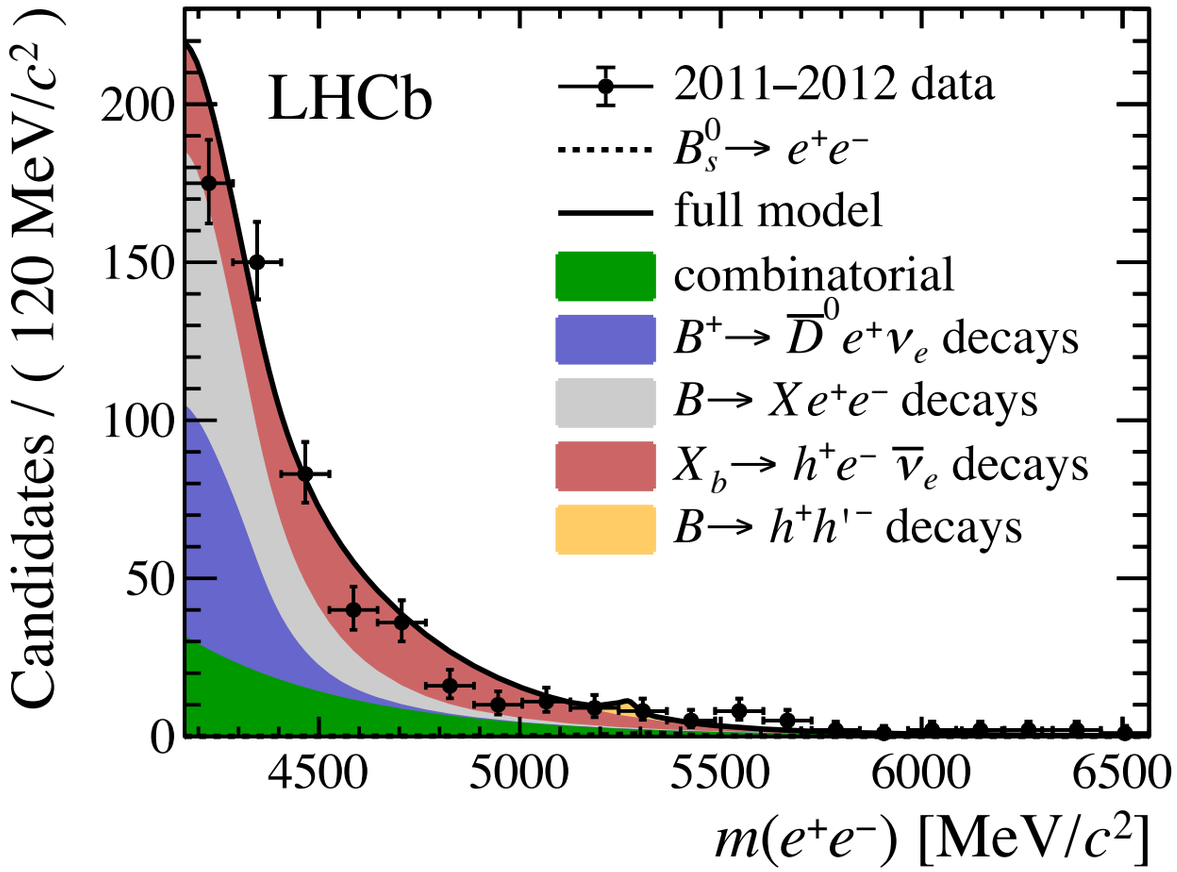


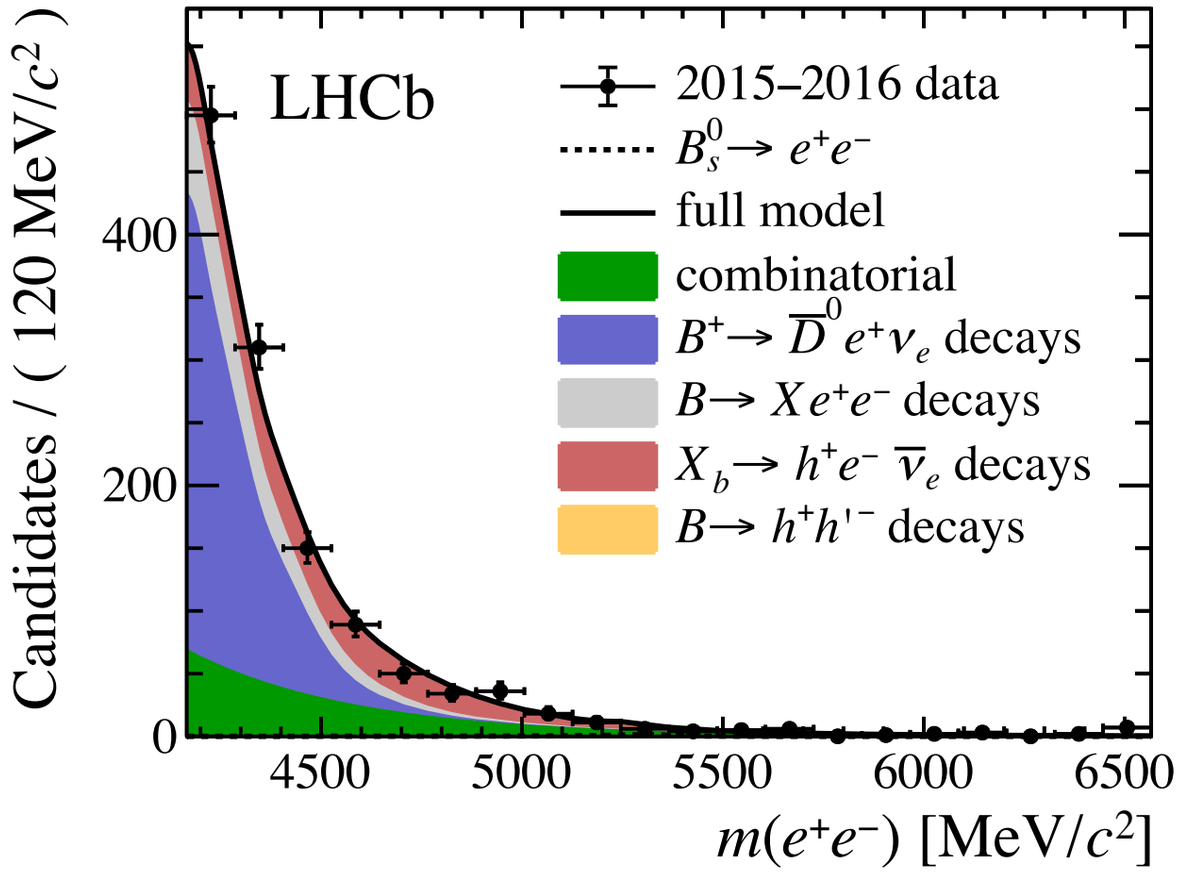
- Purely leptonic final state => precise SM predictions of branching fractions
  - e : $\mathscr{B}_{B^0_s}, \mathscr{B}_{B^0} = (8.06 \pm 0.36) \times 10^{-14}, (2.41 \pm 0.13) \times 10^{-15}$ [JHEP 10 (2019) 232]
  - μ : $\mathscr{B}_{B^0_s}, \mathscr{B}_{B^0} = (3.66 \pm 0.14) \times 10^{-9}, (1.03 \pm 0.05) \times 10^{-10}$ [JHEP 10 (2019) 232]
  - τ : $\mathscr{B}_{B^0_s}, \mathscr{B}_{B^0} = (7.73 \pm 0.49) \times 10^{-7}, (2.22 \pm 0.19) \times 10^{-8}$ [PRL 112 (2014) 101801]
- Non-SM contributions can modify branching fractions [e.g. JHEP 05 (2017) 156]
- Experimental status at the LHCb
  - e : branching fraction limits set [PRL 124 (2020) 211802]
  - μ : B^0_s mode observed and studied, limit set for B^0 [arXiv:2108.09283(4)]
  - τ : branching fraction limits set [PRL 118 (2017) 251802]

Rare decays — $B^0_{(s)} \to e^+e^-$

[PRL 124 (2020) 211802]

- Analysed 5.0fb^{-1} of data from Run 1 (2011-2012) and part of Run 2 (2015-2016)
- Branching fraction measured relative to normalisation channel $B^+ \to J/\psi K^+$



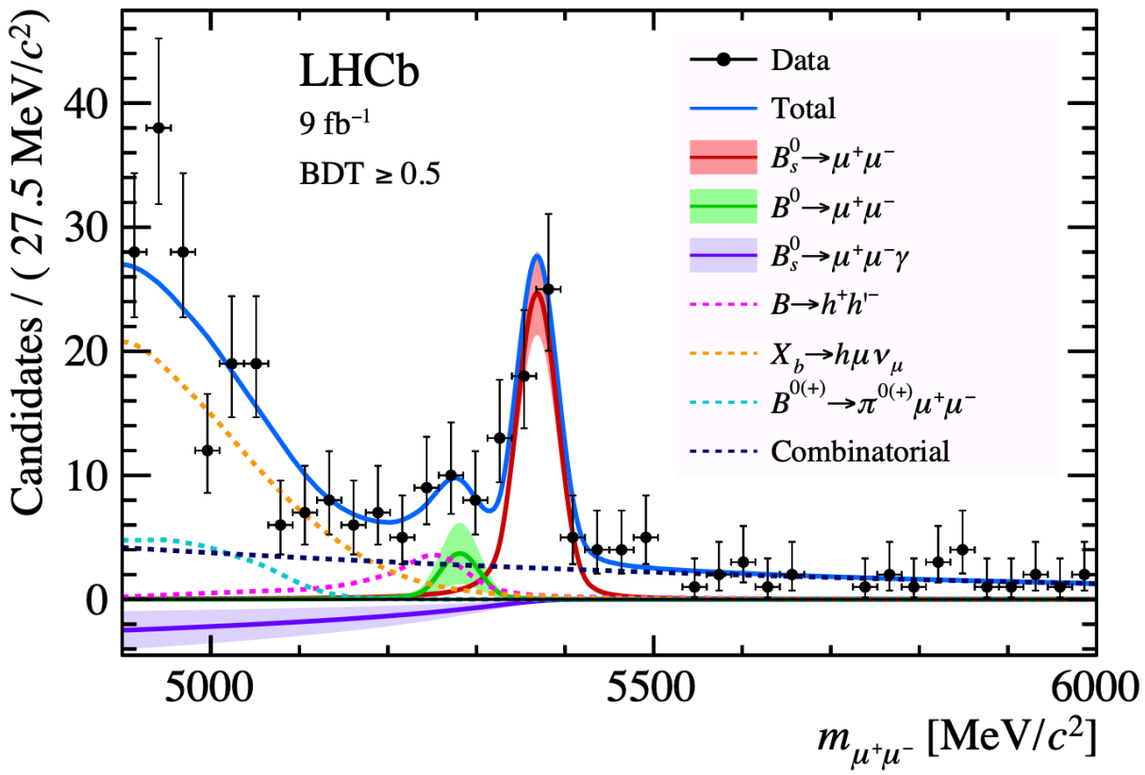


- No observation, branching fraction limits obtained at 90 (95%) CL (assuming no contribution from the other mode):
  - $\mathcal{B}(B^0_s \to e^+e^-) < 9.4(11.2) \times 10^{-9}$
  - $\mathcal{B}(B^0 \to e^+e^-) < 2.5(3.0) \times 10^{-9}$
- Order of magnitude improvement compared to previous result [arXiv:0901.3803]

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

[arXiv:2108.09283(4)]

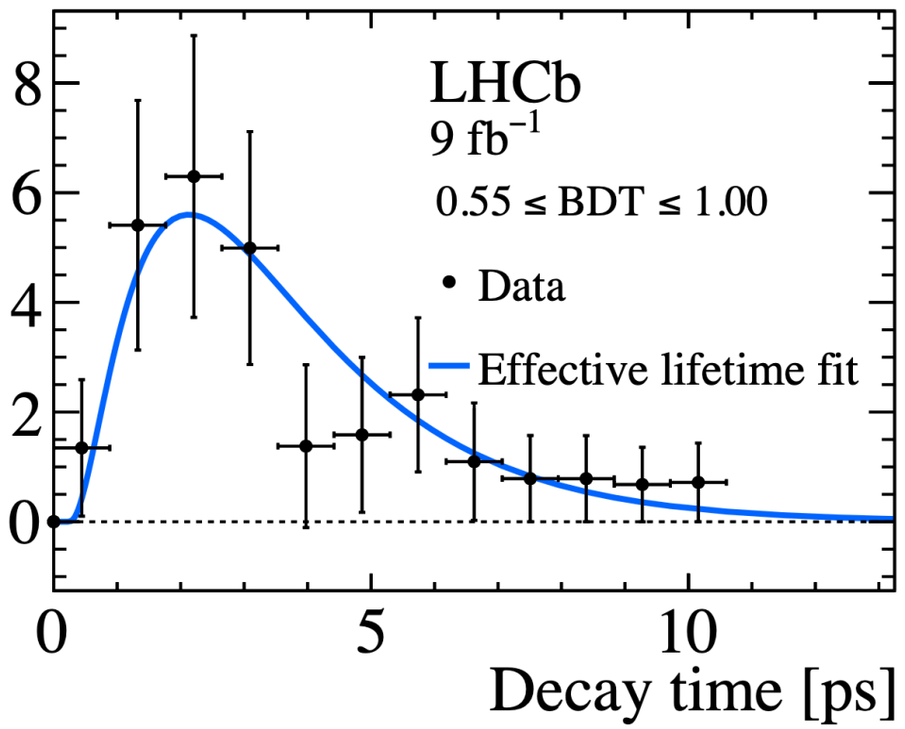
- $B^0_s \to \mu^+\mu^-$ measurements made using 8.7fb^{-1} of Run 1 and Run 2 data
- Searched for $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-\gamma$
- Obtained/set upper limits at 95 % CL:
  - $\mathscr{B}(B^0_s \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$
  - $\mathscr{B}(B^0 \to \mu^+\mu^-) < 2.6 \times 10^{-10}$
  - $\mathscr{B}(B^0_s \to \mu^+\mu^-\gamma) < 2.0 \times 10^{-9}$



- Measured effective lifetime of $B^0_s \to \mu^+\mu^-$,

$$\tau_{\mu^+\mu^-} \equiv \frac{\tau_{B^0_s}}{1-y_s^2}\left[\frac{1+2A^{\mu\mu}_{\Delta\Gamma_s}y_s+y_s^2}{1+A^{\mu\mu}_{\Delta\Gamma_s}y_s}\right]$$

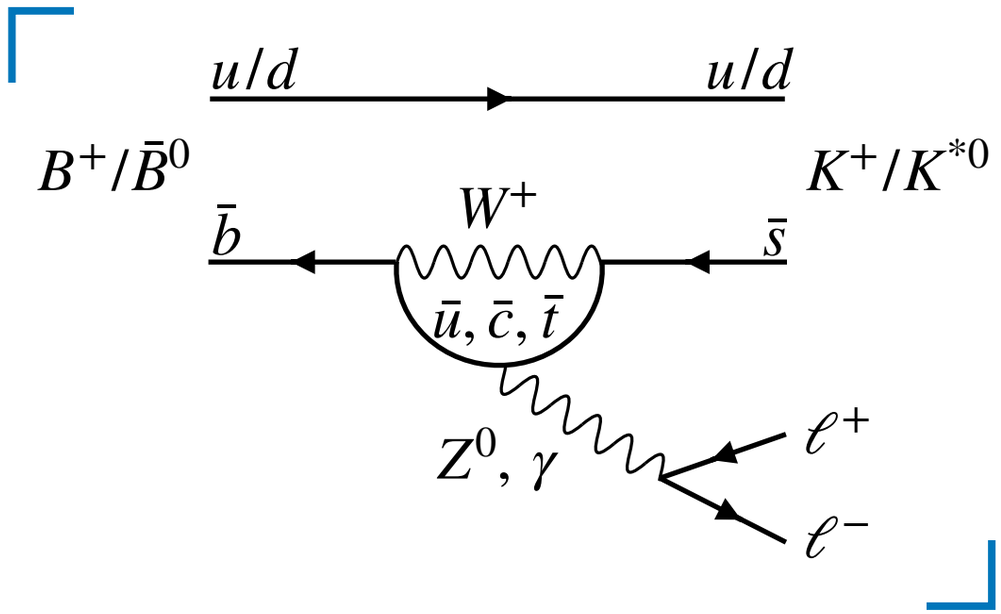
- Determined $\tau_{\mu^+\mu^-} = (2.07 \pm 0.29 \pm 0.03)$ ps
- All results are in agreement with the SM

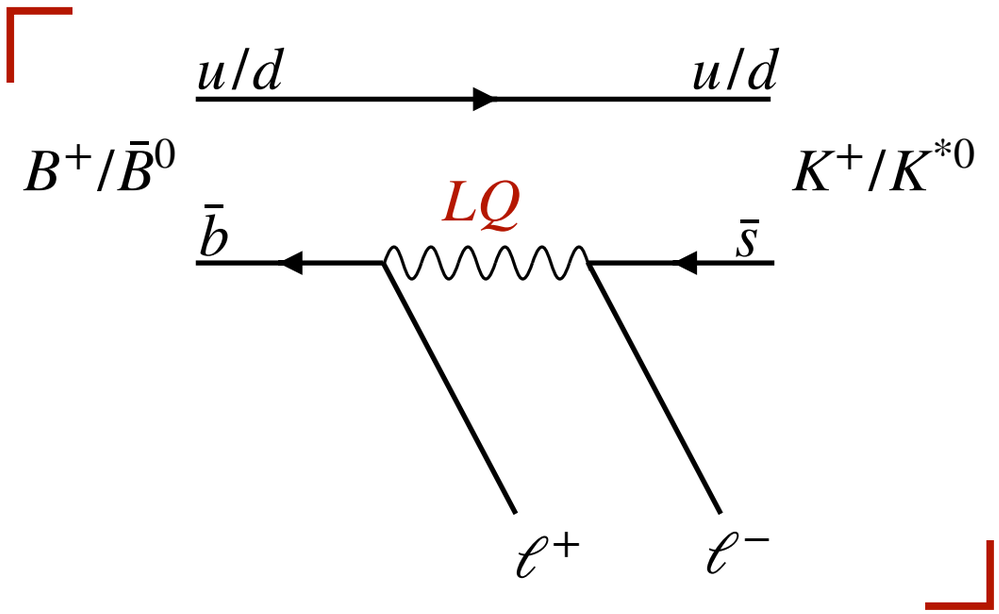


Rare decays — $b \to s\ell^+\ell^-$

- Recent measurements of $b \to s\ell^+\ell^-$ processes hint at deviation from SM in branching fractions, angular observables, and lepton flavour universality (LFU) tests

e.g. $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$ in the SM and a non-SM scenario





Selected measurements involving $b \to s\ell^+\ell^-$ decays (LHCb)

Branching fractions

- $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]
- $\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115] [JHEP 09 (2018) 145]
- $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]
- $B_s^0 \to \phi\mu^+\mu^-$ [arXiv:2105.14007]

Angular

- $B^0 \to K^{*0}\mu^+\mu^-$ [PRL 125 (2020) 011802]
- $B^0 \to K^{*+}\mu^+\mu^-$ [PRL 126 (2021) 161802]
- $B_s^0 \to \phi\mu^+\mu^-$ [arXiv:2107.13428]

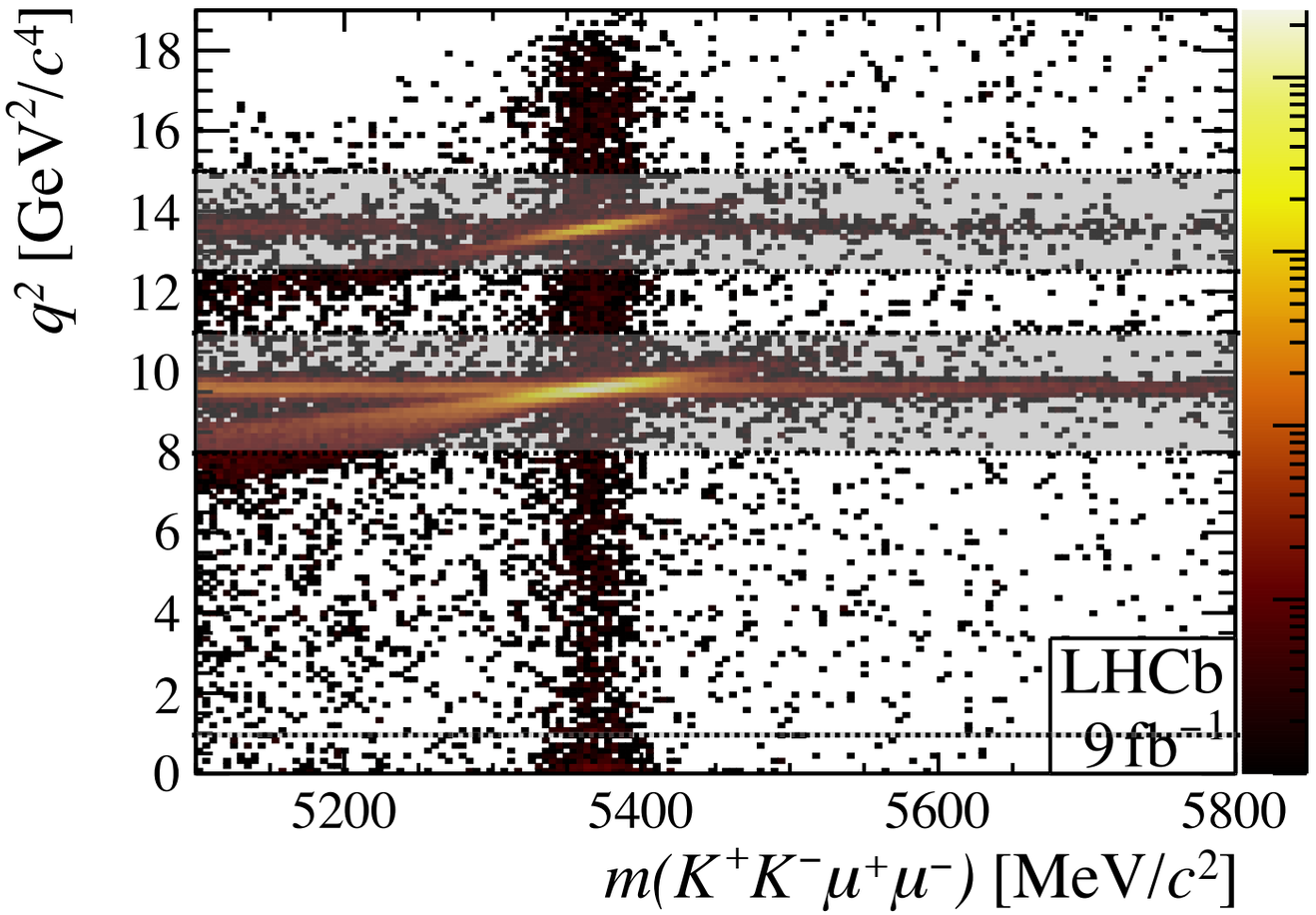
LFU

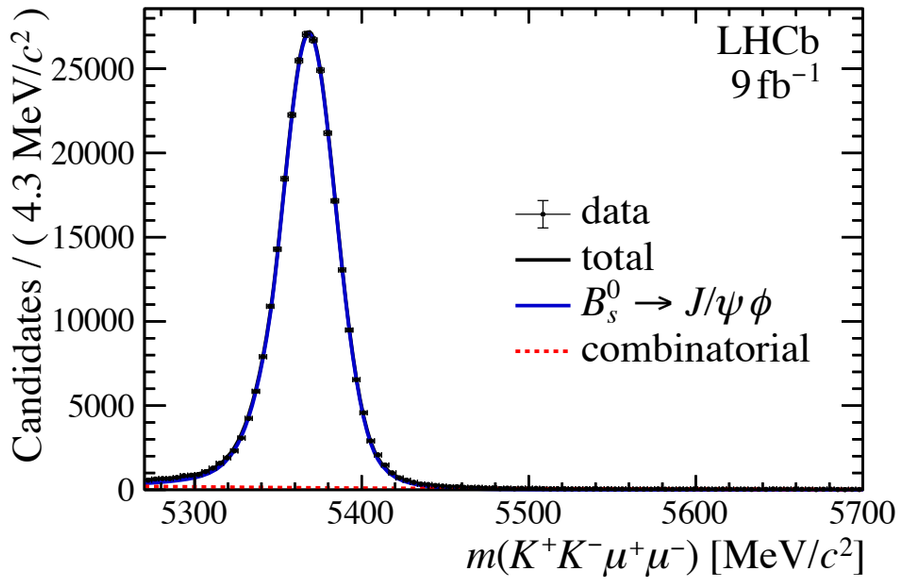
- $B^0 \to K^{*0}\ell^+\ell^-$ $(R_{K^{*0}})$ [JHEP 08 (2017) 055]
- $\Lambda_b^0 \to pK^-\ell^+\ell^-$ (R_{pK}) [JHEP 05 (2020) 040]
- $B^+ \to K^+\ell^+\ell^-$ (R_K) [arXiv:2103.11769]

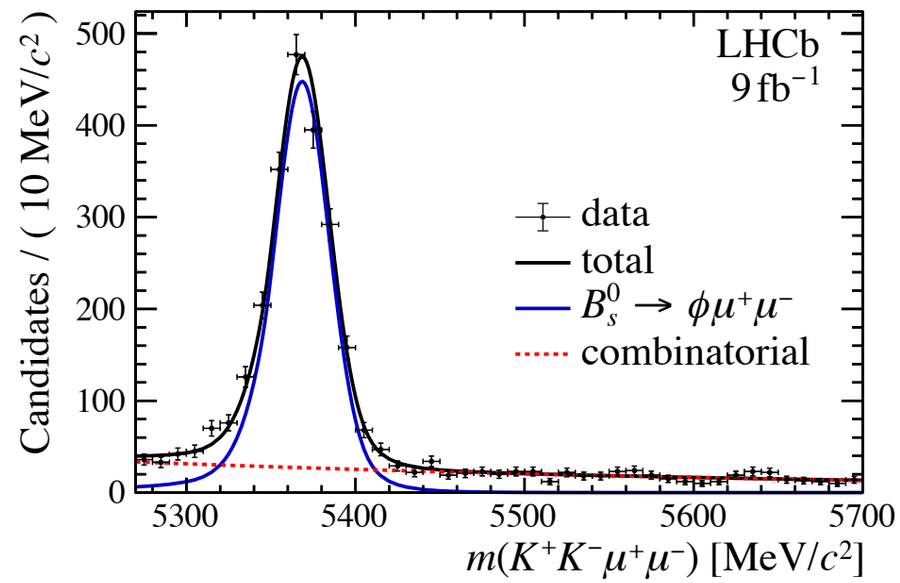
Branching fraction — $B_s^0 \to \phi\mu^+\mu^-$

[arXiv:2105.14007]

- Measurement made using full Run 1 and Run 2 data (9fb^{-1})
- Veto q^2 (dimuon invariant mass squared) regions dominated by tree-level $b \to c\bar{c}s$ modes ($B_s^0 \to J/\psi\phi$ used as normalisation mode) and $B_s^0 \to \phi(\to \mu^+\mu^-)\phi$ decays
- Cut within 12MeV/c^2 of the known ϕ mass



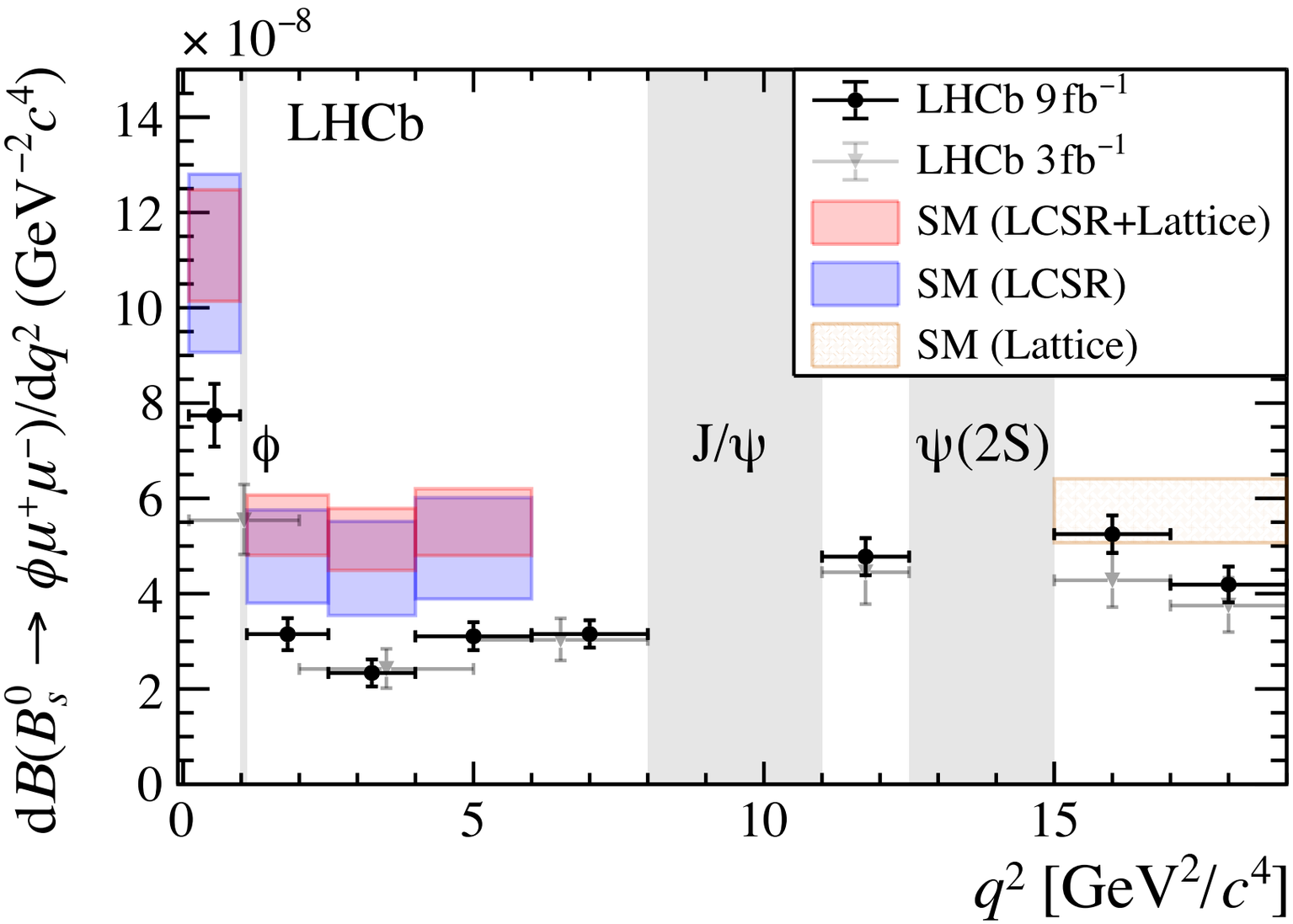




Branching fraction — $B_s^0 \to \phi\mu^+\mu^-$

[arXiv:2105.14007]

- Differential branching fraction determined in intervals of q^2, relative to normalisation mode, via extended ML fit



[PRL 112 (2014) 212003]
[PoS Lattice 2014 372]

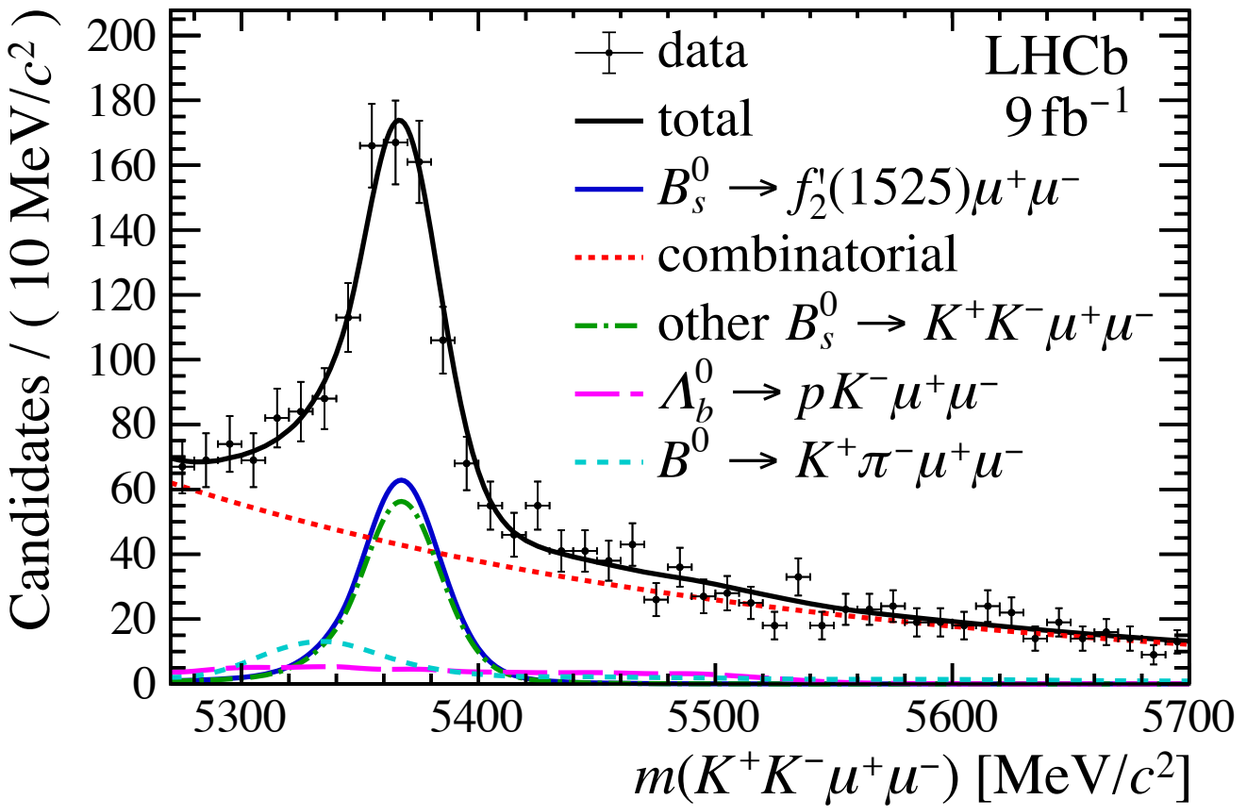
[JHEP 08 (2016) 098]
[EPJC 75 (2015) 382]

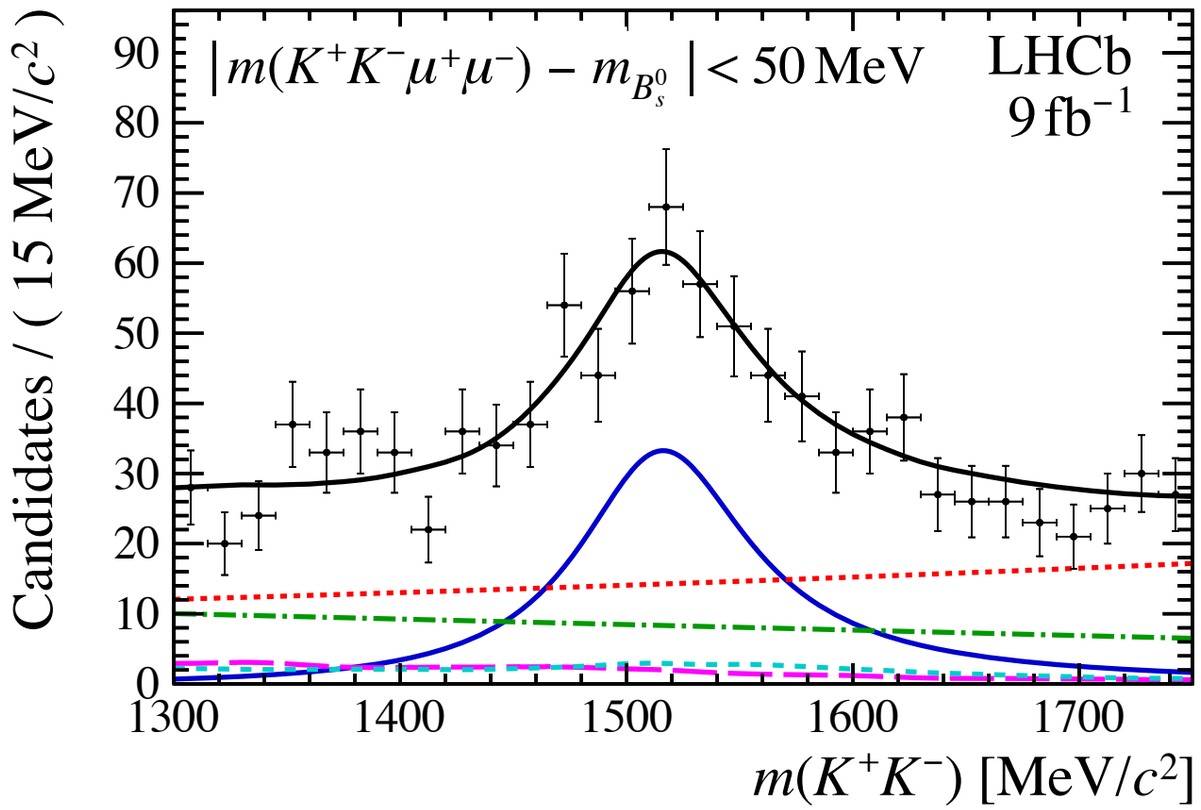
- $$\frac{d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{dq^2} = (2.88 \pm 0.22) \times 10^{-8}\ (\mathrm{GeV}^2/c^4)^{-1}\ (\text{for } [q^2 \in 1.1 - 6.0\ \mathrm{GeV}^2/c^4])$$

=> 3.6σ (LCSR + Lattice) and 1.8σ (LCSR only) tension with SM

Branching fraction — $B_s^0 \to f_2'(1525)\mu^+\mu^-$ [arXiv:2105.14007]

- Similar strategy used, differences include: cut of 225MeV/c^2 around wider f_2' resonance, separate BDT optimisation, additional backgrounds (wider $m(K^+K^-)$ window)
- Fit $m(K^+K^-)$ to control contributions from S-wave and other resonances e.g. ϕ and $\phi(1680)$





- First observation with 9σ significance
- Measured $\mathcal{B}(B_s^0 \to f_2'\mu^+\mu^-) = (1.57 \pm 0.19_{\text{stat.}} \pm 0.06_{\text{syst.}} \pm 0.06_{q^2\text{ extrap.}} \pm 0.08_{\text{norm.}}) \times 10^{-7}$
- Result in agreement with SM predictions

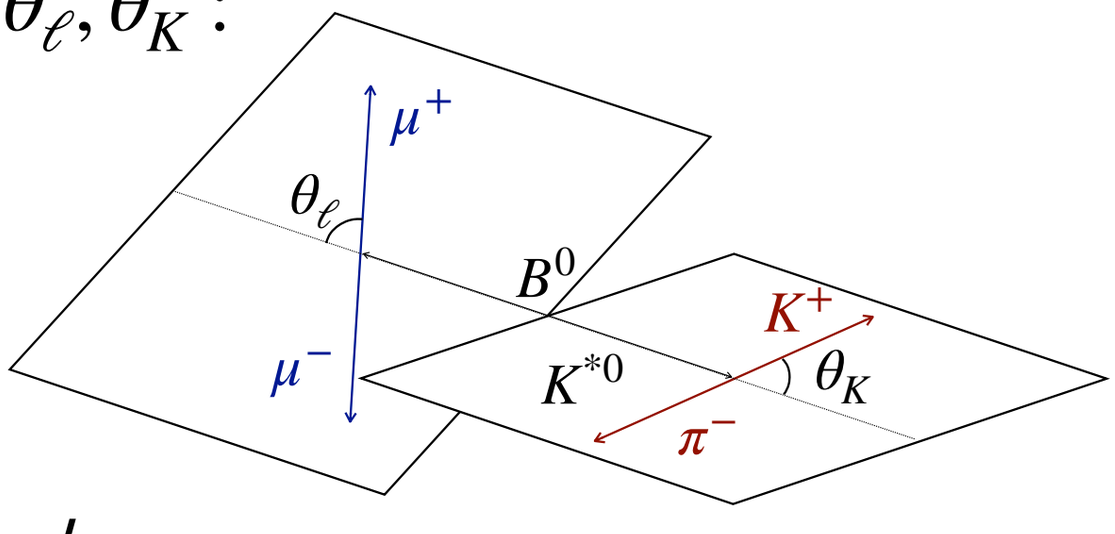
Angular analysis — $B^0 \to K^{*0}\mu^+\mu^-$

[PRL 125 (2020) 011802]

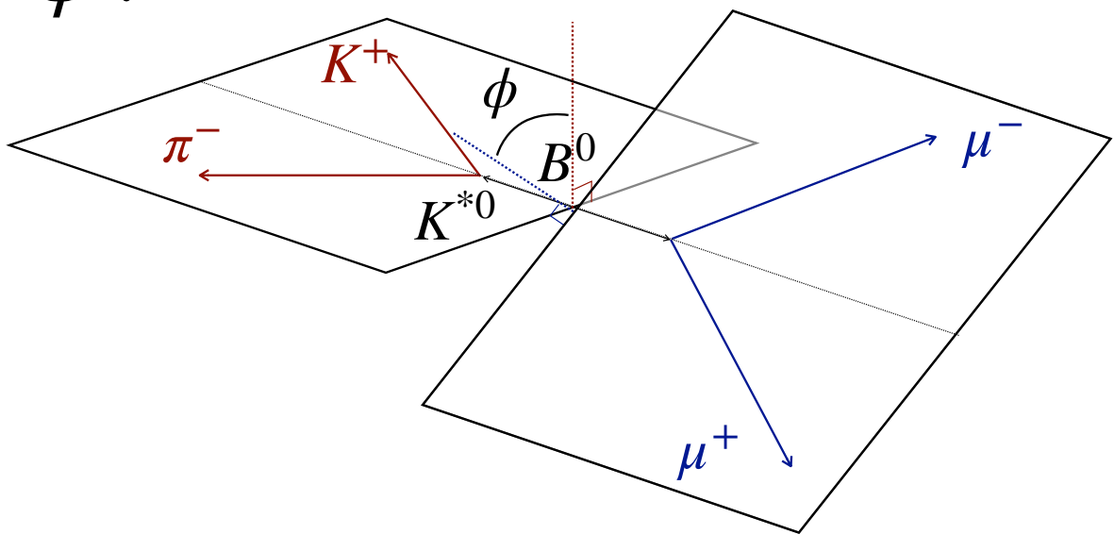
- The final state of $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ can be described by q^2, and the three decay angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K - F_L\cos^2\theta_K\cos2\theta_\ell$$
$$+ S_3\sin^2\theta_K\sin^2\theta_\ell\cos2\phi + S_4\sin2\theta_K\sin2\theta_\ell\cos\phi$$
$$+ S_5\sin2\theta_K\sin\theta_\ell\cos\phi + \frac{4}{3}A_{FB}\sin^2\theta_K\cos\theta_\ell$$
$$+ S_7\sin2\theta_K\sin\theta_\ell\sin\phi + S_8\sin2\theta_K\sin2\theta_\ell\sin\phi$$
$$+ S_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi\Big]$$

θ_ℓ, θ_K :



ϕ :



F_L, A_{FB}, S_i — angular observables sensitive to underlying physics

P_i' — alternative basis with reduced form factor uncertainties, e.g.

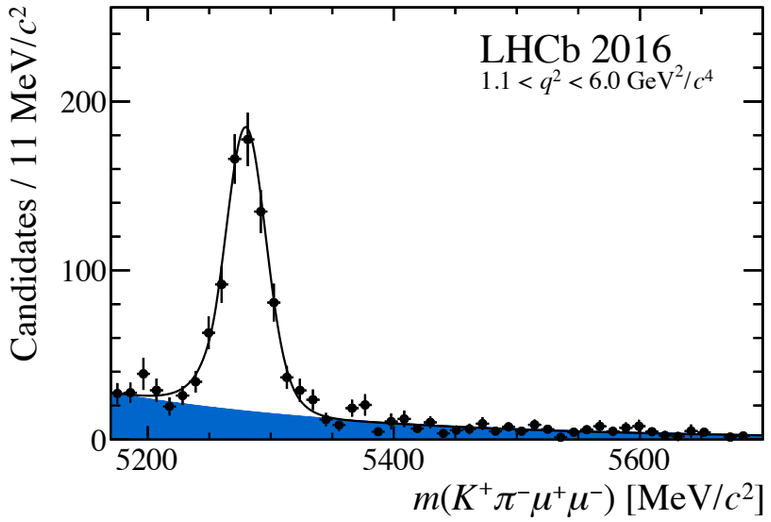
$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

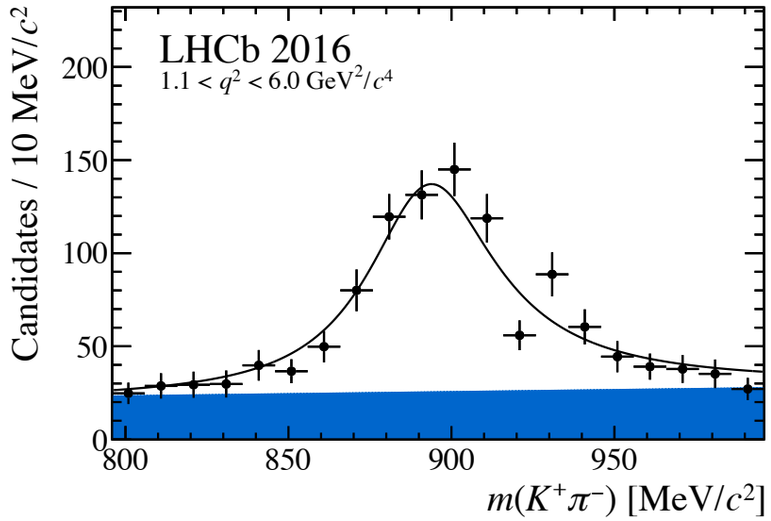
[JHEP, 05 (2013) 137]

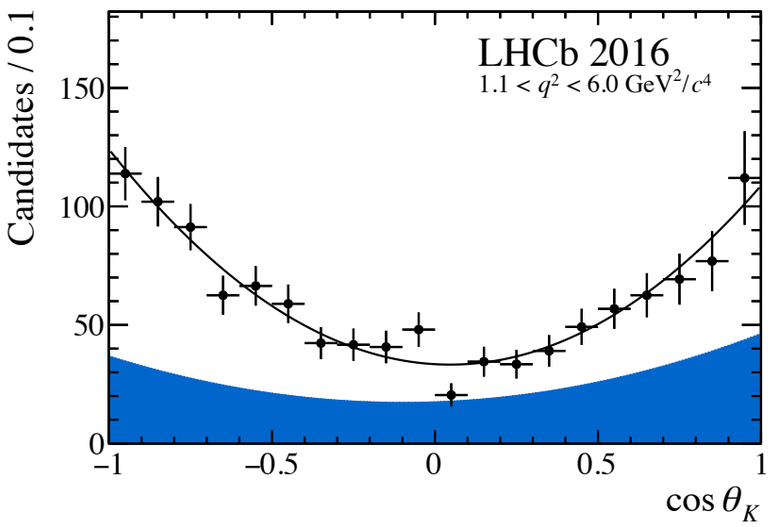
Angular analysis — $B^0 \to K^{*0}\mu^+\mu^-$

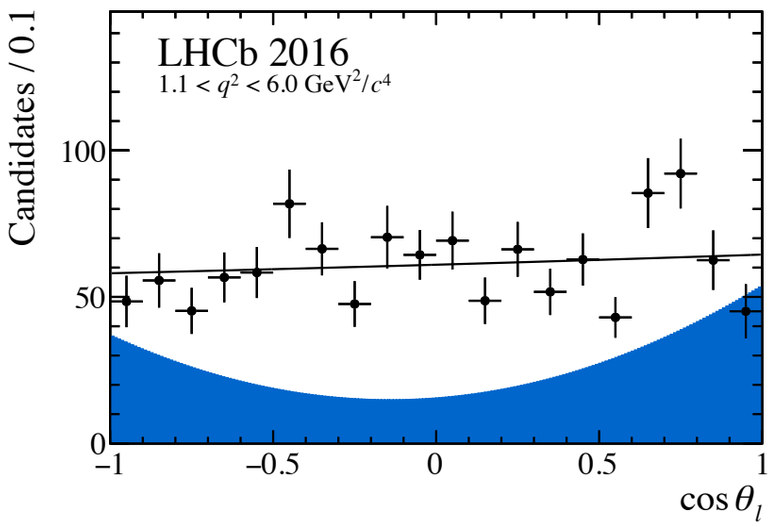
[PRL 125 (2020) 011802]

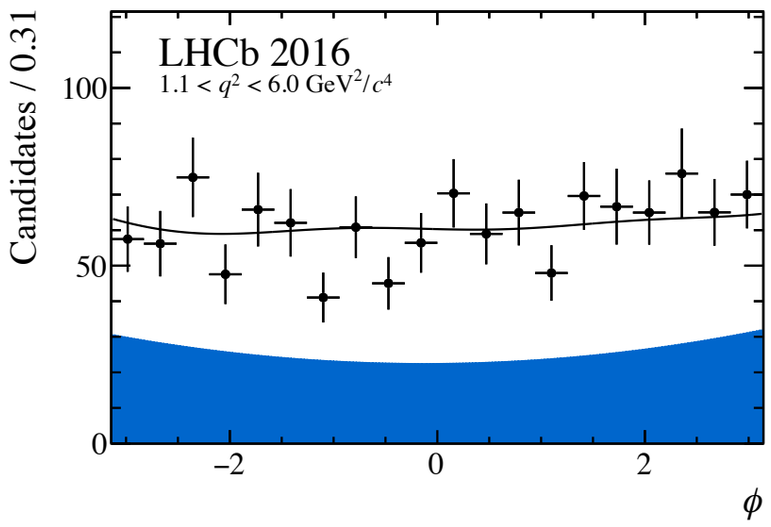
- Most recent update using Run 1 + 2016 data (4.7fb^{-1})
- Measurements made in $q^2 \in ([0.1, 0.98], [1.1, 6.0]$, and $[15.0, 19.0])$ GeV^2/c^4
- Angular distributions corrected using acceptance function ($\epsilon(\vec{\Omega}, q^2)$)
- Five dimensional ($\vec{\Omega}$, $m(K^+\pi^-\mu^+\mu^-)$, $m(K^+\pi^-)$) simultaneous fit to Run 1 + 2016 samples
- Inclusion of $m(K^+\pi^-)$ allows for control over S-wave contribution









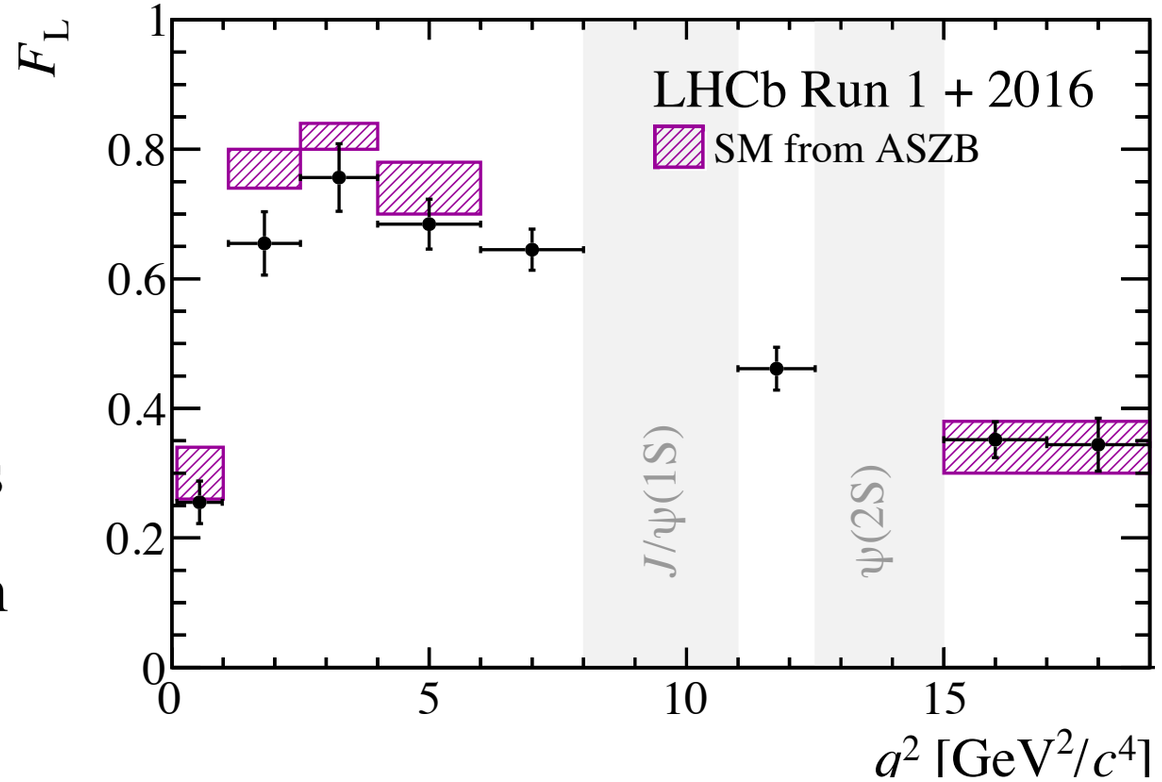


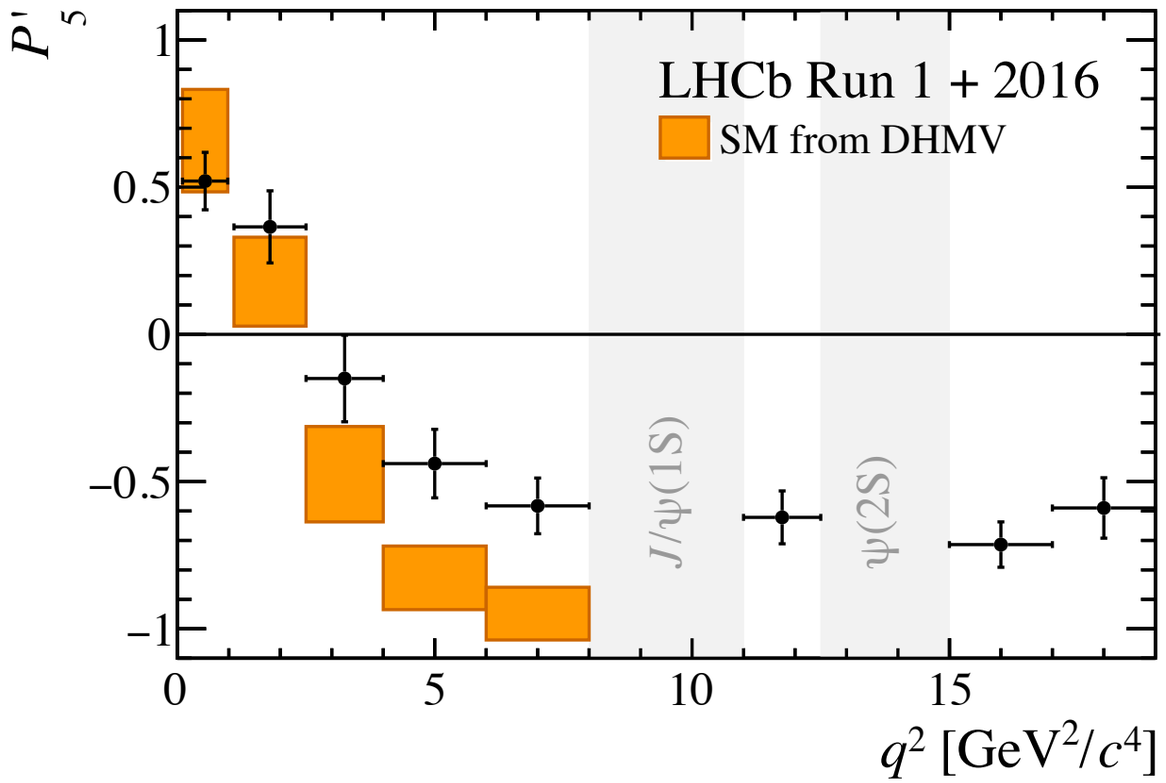
Angular analysis — $B^0 \to K^{*0}\mu^+\mu^-$

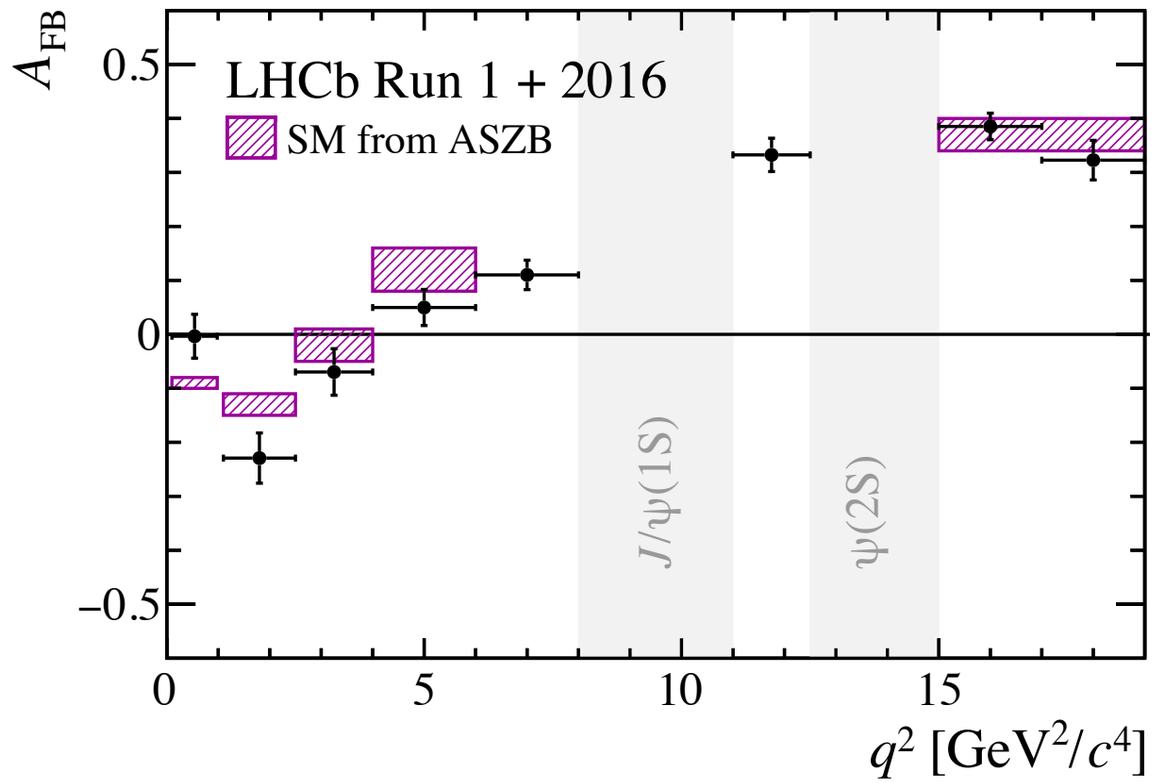
[PRL 125 (2020) 011802]

- Analysis procedure cross-checked using control mode $B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-)$

  => found good agreement with existing measurements
- Agreement good between Run 1 and 2016 results
- Generally consistent with SM, mild tensions seen in F_L, A_{FB} and P_5'







Angular analysis — $B^0 \to K^{*+}\mu^+\mu^-$ [PRL 126 (2021) 161802]

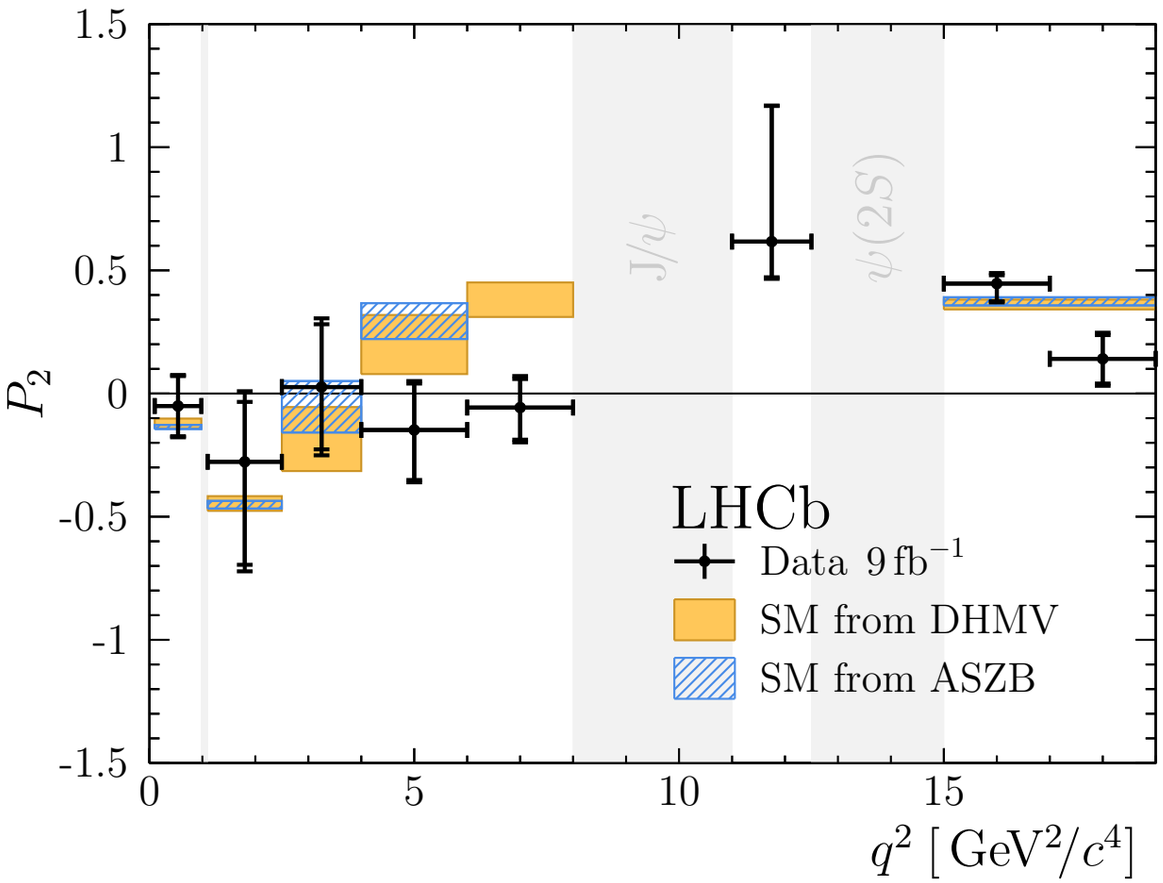
- Analysed full Run 1 and Run 2 data (9fb^{-1})

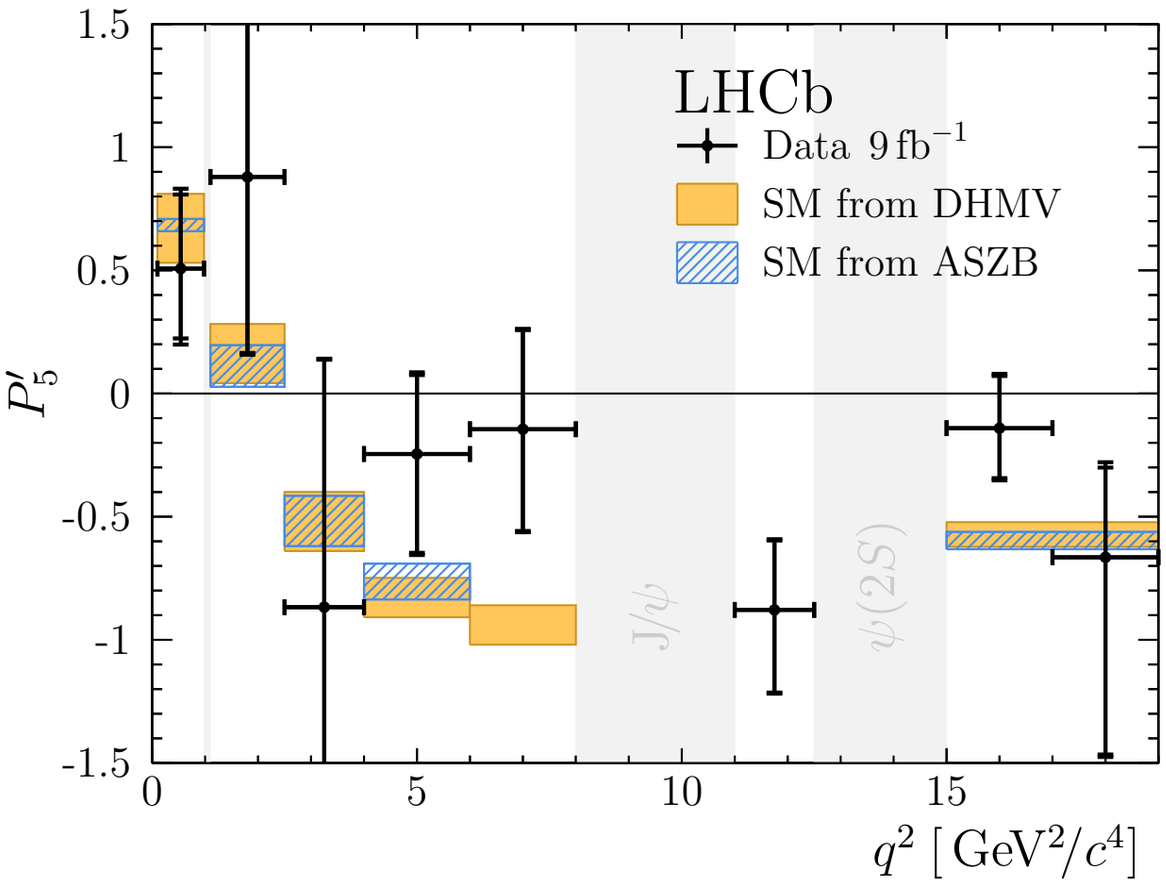
  => first measurement of complete set of observables

- Isospin parter of $B^0 \to K^{*0}\mu^+\mu^-$; similar analysis strategy

- Decay reconstructed via $B^0 \to K^{*+}(\to K^0_S\pi^+)\mu^+\mu^-$ with $K^0_S \to \pi^+\pi^-$

- Apply folding to differential decay rate pdf to increase fit stability



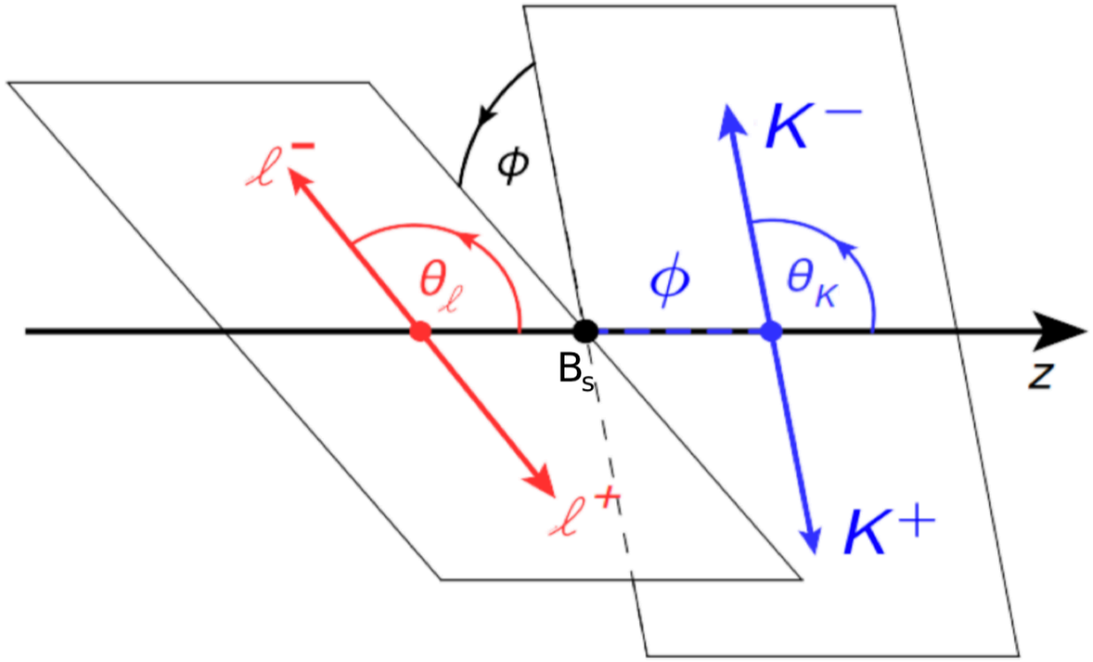


- Results generally in agreement with the SM

Angular analysis — $B_s^0 \to \phi\mu^+\mu^-$ [arXiv:2107.13428]

- Complementary to branching fraction measurement
- Updates previous measurement using 8.4fb^{-1} of data from Run 1 and most of Run 2
- Selection criteria same as that of the branching fraction measurement; analysis strategy similar to that of $B^0 \to K^{*0}\mu^+\mu^-$
- Key difference — final state flavour symmetric ($B_s^0/\bar{B}_s^0$ not distinguished)

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K(1+\frac{1}{3}\cos2\theta_\ell)$$
$$+F_L\cos^2\theta_K - F_L\cos^2\theta_K\cos2\theta_\ell$$
$$+S_3\sin^2\theta_K\sin^2\theta_\ell\cos2\phi + S_4\sin2\theta_K\sin2\theta_\ell\cos\phi$$
$$+A_5\sin2\theta_K\sin\theta_\ell\cos\phi + \frac{4}{3}A_{FB}^{CP}\sin^2\theta_K\cos\theta_\ell$$
$$+S_7\sin2\theta_K\sin\theta_\ell\sin\phi + A_8\sin2\theta_K\sin2\theta_\ell\sin\phi$$
$$+A_9\sin^2\theta_K\sin^2\theta_\ell\sin2\phi\Big]$$



F_L, S_i — CP averaged observables

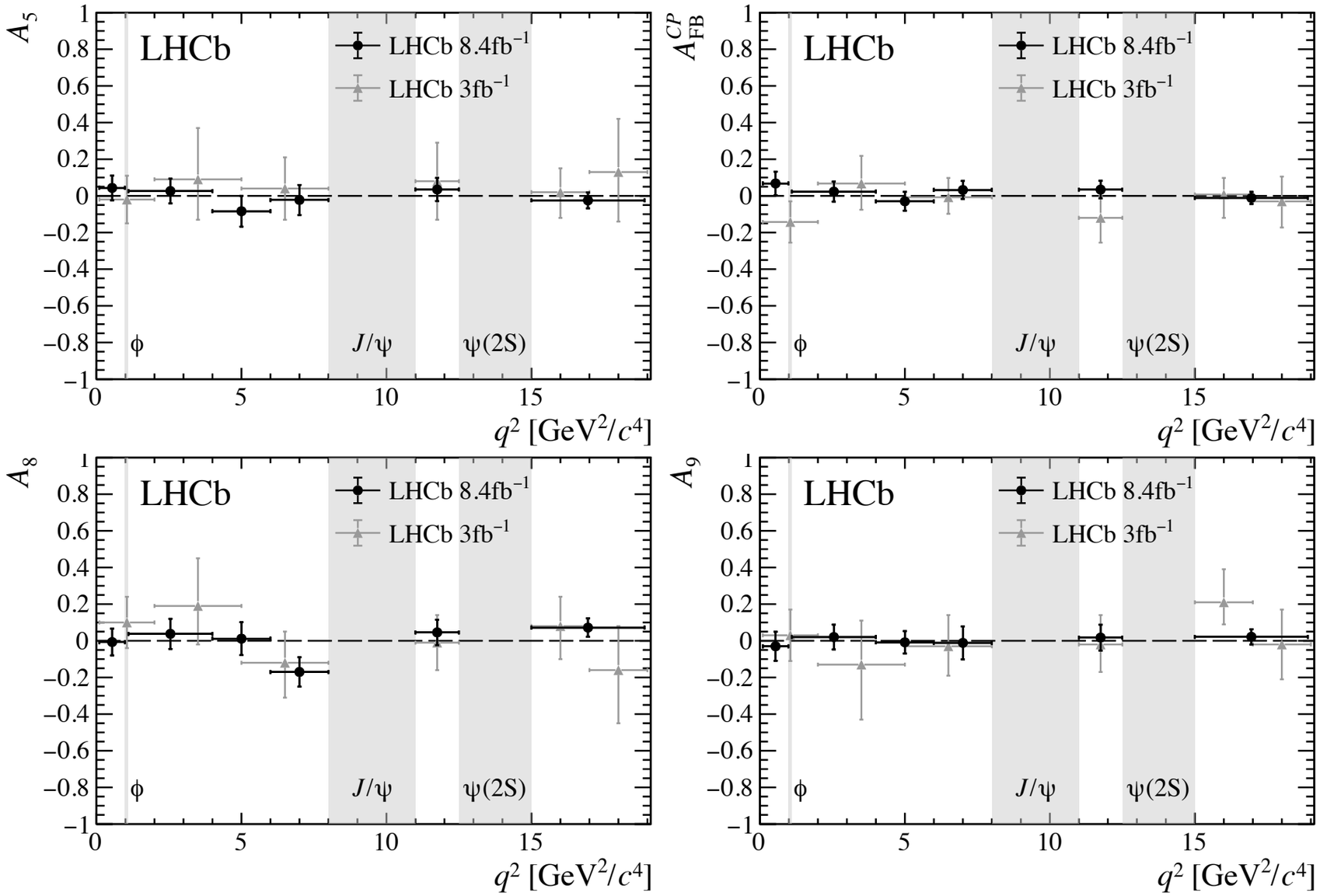
A_{FB}^{CP}, A_i — CP asymmetries

- Some observables including P_5' are not accessible

Angular analysis — $B_s^0 \to \phi\mu^+\mu^-$

[arXiv:2107.13428]

- Observable values determined from simultaneous fit to $m(K^+\pi^-\mu^+\mu^-)$ and $\overrightarrow{\Omega}$ (S-wave treated as systematic uncertainty)
- Results in general good agreement with the SM
- CP asymmetries close to zero (consistent with predictions)
- Mild tension seen in F_L



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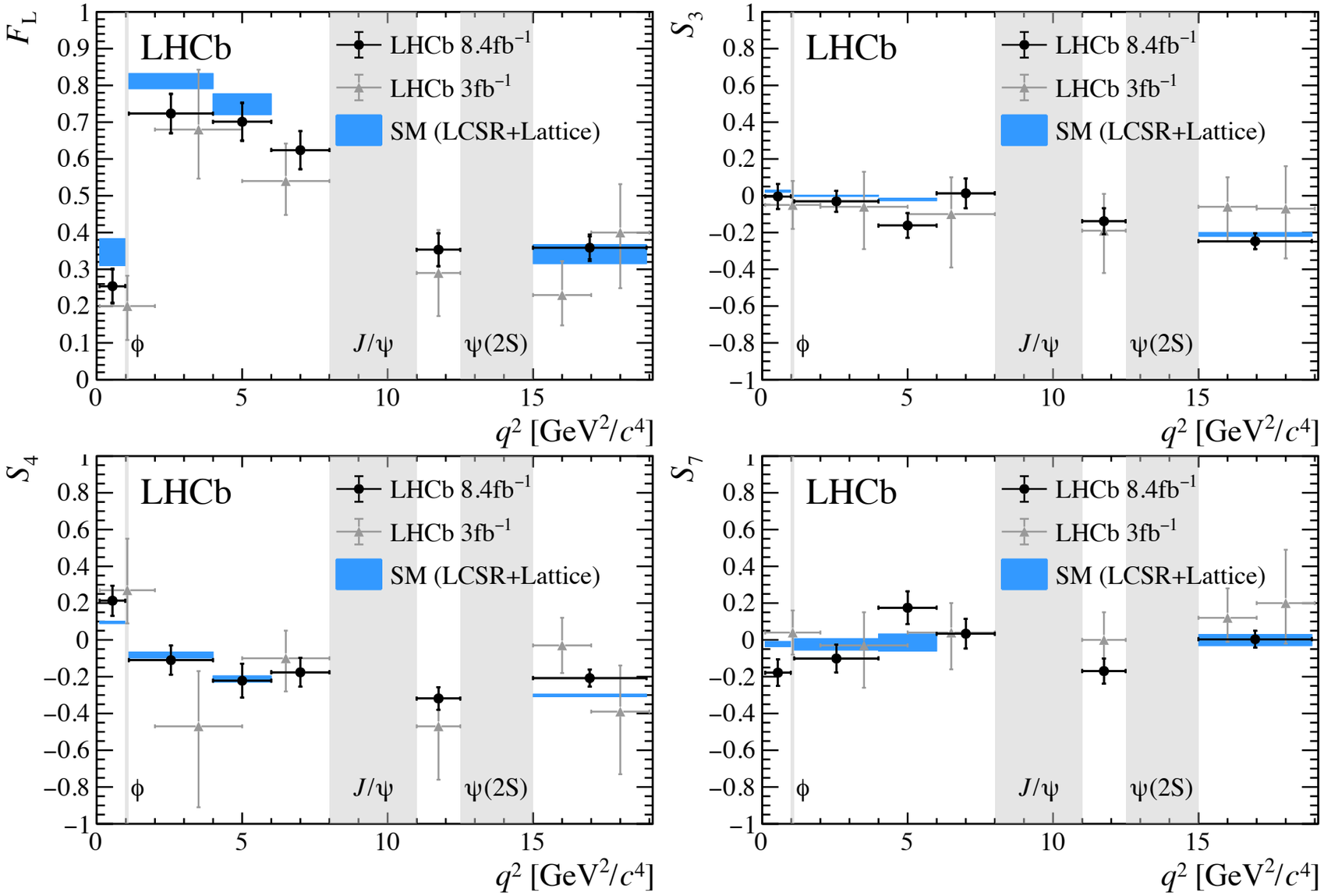


A consistent picture?

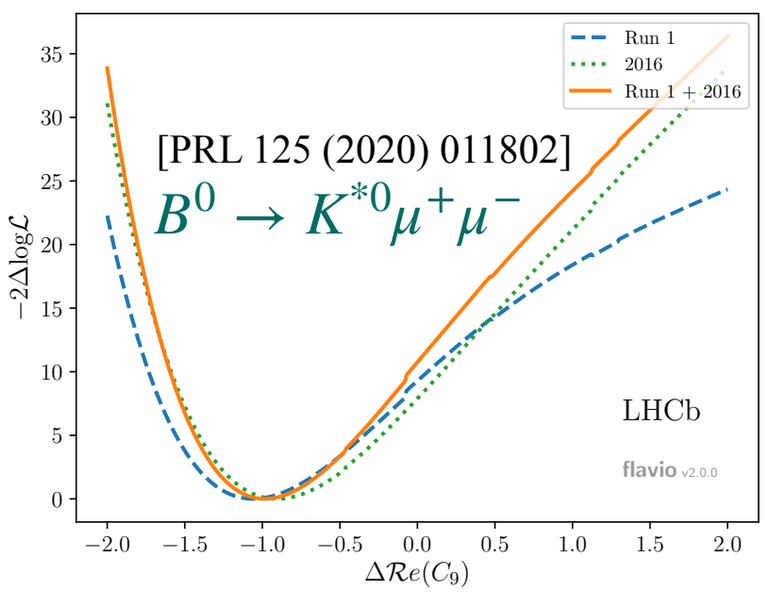
- Rare b decays can be described using effective field theory (model-independent)
- Hamiltonian can be written as an operator product expansion

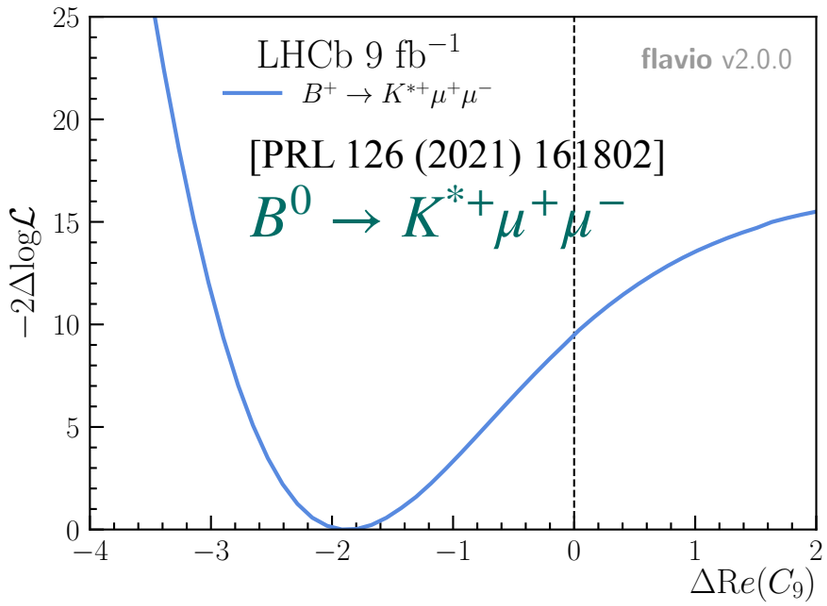
$$\mathscr{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i \boxed{C_i}\,\boxed{\mathcal{O}_i}$$

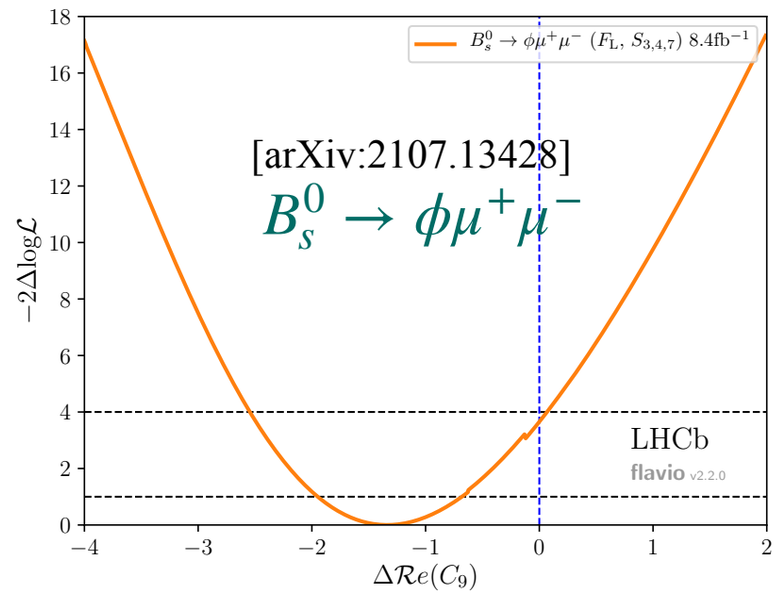
Wilson coefficients ('effective coupling') — Local operators

$$\boxed{C_i = C_i^{\mathrm{SM}} + C_i^{\mathrm{NP}}}$$

- $b \to s\ell^+\ell^-$ processes sensitive to $\mathcal{O}_9$, $\mathcal{O}_{10}$ (EW penguin) and $\mathcal{O}_7$
- Can fit for Wilson coefficients, which can be modified by non-SM contributions
- Fits of $\mathrm{Re}(C_9)$ using Flavio [arXiv:1810.08132] show consistent trend



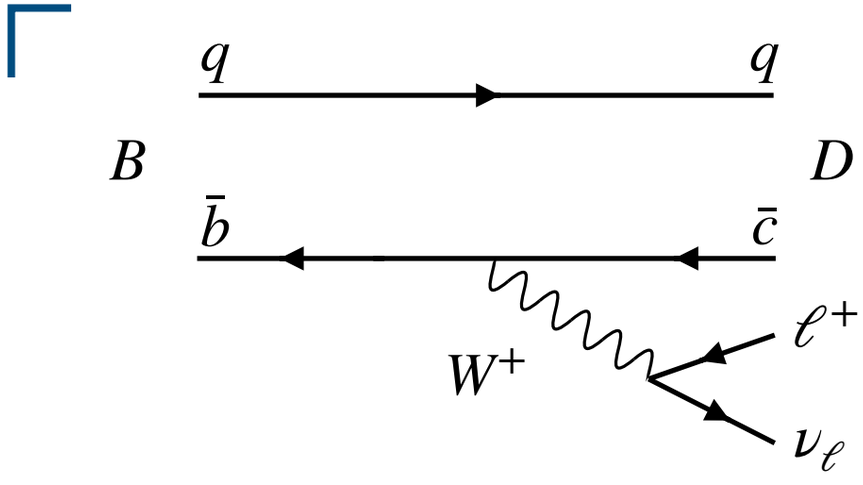


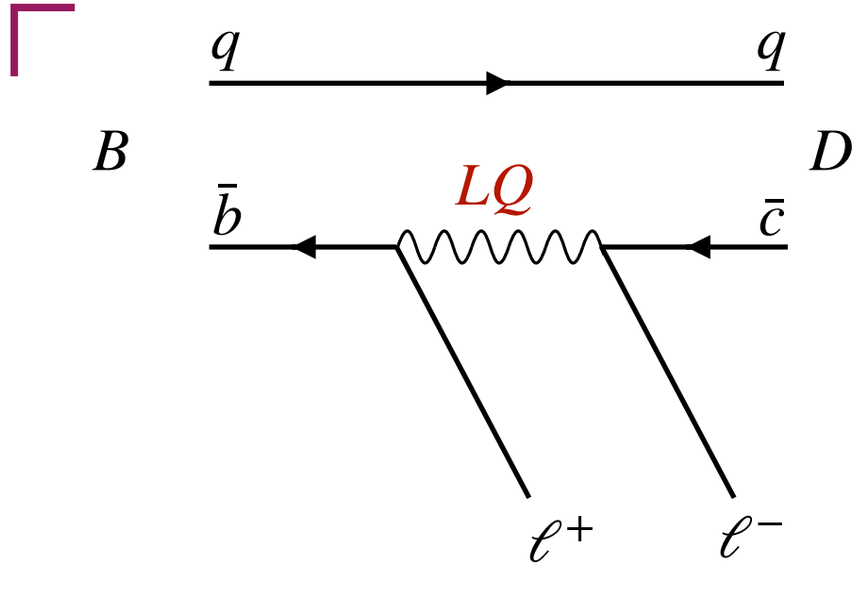


- Negative $\Delta\mathrm{Re}(C_9)$ values preferred over SM hypothesis at the level of $2-3\sigma$

Semileptonic decays

- Semileptonic decays featuring $b \to c\ell\nu$ are tree-level processes
- Involved in several tests of LFU; some results show mild tension with SM





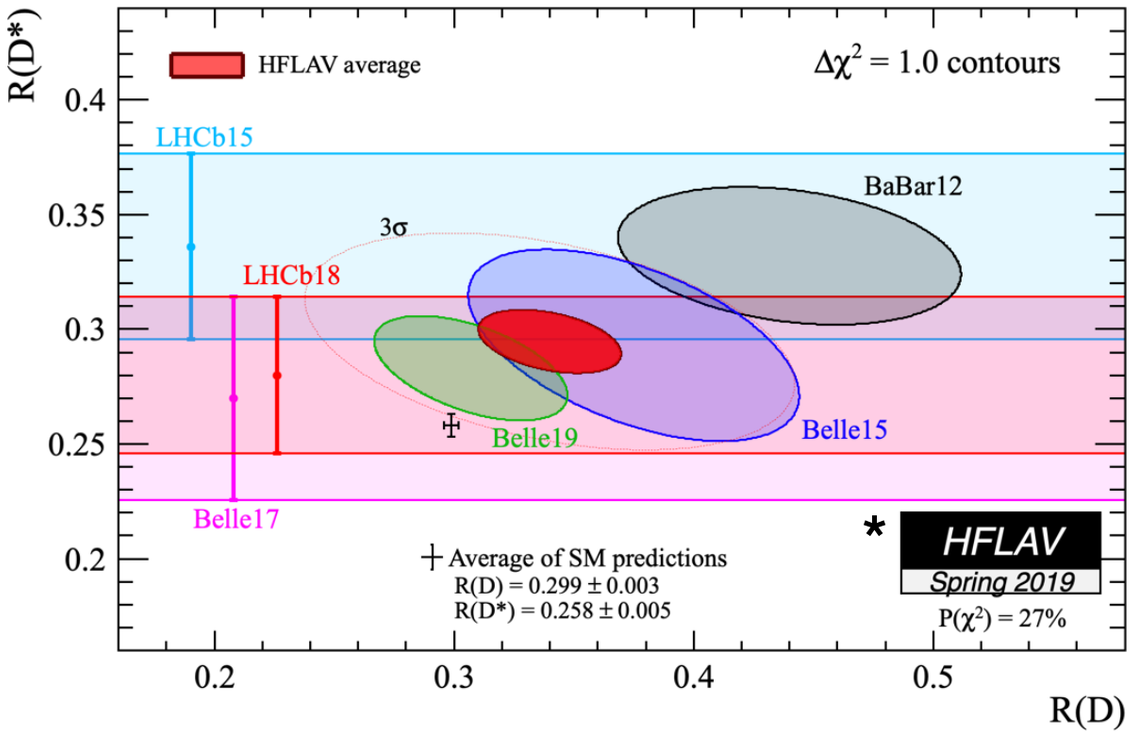
- LFU test can be out by measuring ratios of branching fractions — decays involving τ sensitive to non-SM contributions:

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau\nu)}{\mathcal{B}(H_b \to H_c \mu\nu)} \qquad \begin{matrix} H_b = B^0, B^+, B_s, \Lambda_b^0 \\ H_c = D^*, D^+, D_s, \Lambda_c^0, J/\psi \end{matrix}$$

- τ decay modes used include $\tau^- \to \mu^-\nu_\mu\nu_\tau$ (leptonic) and $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$ (hadronic)
- Measurement challenging as neutrinos are not reconstructed (also B kinematics not known)

Semileptonic decays

- All measurements made using Run 1 data only
- Current combination of $R(D^{(*)})$ results (with Belle and BaBar) show 3σ tension with SM



$$R(D^{*-}) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{*-}\tau\nu)}{\mathcal{B}(\bar{B}^0 \to D^{*-}\mu\nu)} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$$

$\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$ / $\tau^+ \to \pi^+\pi^-\pi^+\pi^0\bar{\nu}_\tau$

[PRL 120 (2018) 171802]

$$R(J/\psi) \equiv \frac{\mathcal{B}(\bar{B}_c^+ \to J/\psi\tau\nu)}{\mathcal{B}(\bar{B}_c^+ \to J/\psi\mu\nu)} = 0.71 \pm 0.17 \pm 0.18$$

[PRL 120 (2018) 121801]

- Analysis in progress using Run 1 and 2 data include: $R(D^+)$, $R(D^{**})$, $R(D_s^*)$, $R(J/\psi)$, $R(\Lambda_c)$, combined measurement of $R(D^*)$ and $R(D^0)$, and $R(D^*)$ with $\ell = e, \mu$
- Angular analyses are also underway, they include
  - $B \to D^*\mu(\tau)\nu$
  - $\Lambda_b \to \Lambda_c\mu\nu$ initial studies — [JHEP 12 (2019) 148]

*HFLAV; incl. [PRL 115 (2015) 111803], [PRD 97 (2018) 072013], [PRL 120 (2018) 171802], [arXiv:1904.08794], [PRL 109 (2012) 101802], [PRD 88 (2013) 072012], [PRD 92 (2015) 072014], [PRL 118 (2017) 211801], [PRD 97 (2018) 012004]

Summary

- Rare and semileptonic decays of b-hadrons — laboratory for precision tests of the SM, and search for non-SM effects
- Several recent results released by LHCb
- $B^0_{(s)} \to \ell^+\ell^-$
  - $B^0_s \to \mu^+\mu^-$ measurements and searches for $B^0 \to \mu^+\mu^-/B^0_s \to \mu^+\mu^-\gamma$ [arXiv:2108.09283(4)]
  - Search for $B^0_{(s)} \to e^+e^-$ [PRL 124 (2020) 211802]
- $b \to s\ell^+\ell^-$
  - Measurement of $\mathcal{B}(B^0_s \to \phi\mu^+\mu^-)$ (3.6σ tension with SM) [arXiv:2105.14007]
  - First observation of $B^0_s \to f'_2(1525)\mu^+\mu^-$ (9σ significance) [arXiv:2105.14007]
  - Angular analyses ($B^0 \to K^{*0}\mu^+\mu^-$, $B^0 \to K^{*+}\mu^+\mu^-$, $B^0_s \to \phi\mu^+\mu^-$) show mild tension with SM; hint at consistent picture [PRL 125 (2020) 011802], [PRL 126 (2021) 161802], [arXiv:2107.13428]
- Many analyses in progress — strong focus on the clarification of the anomalies