News from the flavour sector

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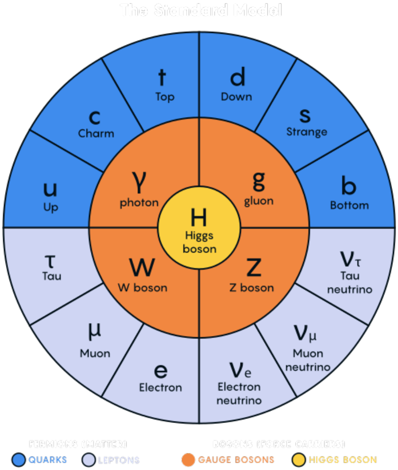
1 Outline

1 Flavour physics



- Different flavours of quarks and leptons
- We have three generations of fermions
- In the Standard Model (SM), distinguished only by the couplings to the Higgs field
- Why three generations?

2 Outline

2 Lepton universality

- Lepton Flavour Universality (LFU) hypothesis: equal gauge bosons couplings to leptons
- Well tested in weak couplings

$Z \to \ell^+\ell^-$

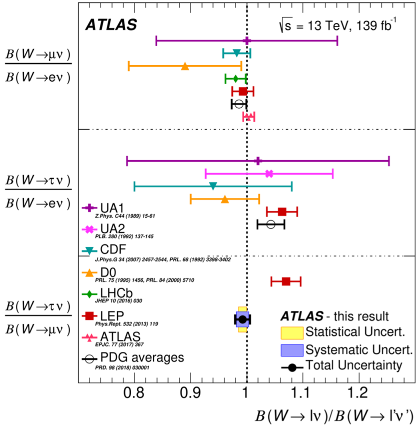
$$\frac{\Gamma_{Z\to\mu^+\mu^-}}{\Gamma_{Z\to e^+e^-}} = 1.0009 \pm 0.0028$$

$$\frac{\Gamma_{Z\to\tau^+\tau^-}}{\Gamma_{Z\to\mu^+\mu^-}} = 1.0019 \pm 0.0032$$

▸ Phys. Rept. 427 (2006) 257]

▸ Nature Physics 17, 813-818 (2021)]]

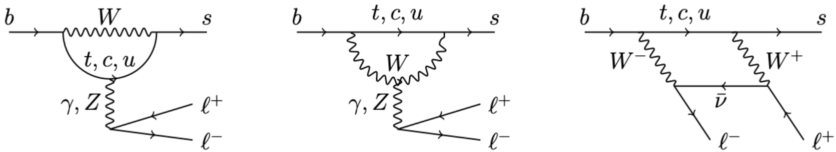
$W \to \ell\nu$



- Not so well tested in heavy quark decays
  - $b \to s\ell\ell$
  - $b \to c\ell\nu$

3 $b \to s\ell\ell$

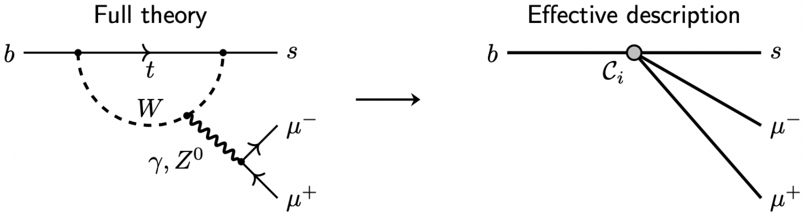
- $b \to s\ell\ell$ decays proceed via FCNC transitions that only occur at loop order in the Standard Model



- Hadronize in many different channels: $B \to K\ell\ell$, $B_s \to \mu\mu$, $B_s \to \phi\ell\ell$
- Excellent probe for New Physics
- New particles can contribute to loop or tree level diagrams:
  $\to$ introduce changes in decay rates and modified angular distributions
- Possible NP contributions are from supersymmetry leptoquarks or heavy gauge bosons

3 $b \to s\ell\ell$: Effective field theory

- Assume the interaction is point like



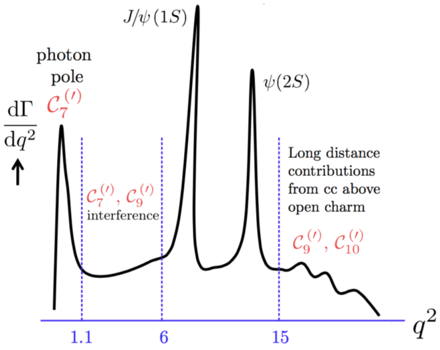
- Effective field theory provides model independent description

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha_e}{4\pi} \sum C_i O_i + C_i' O_i'$$

C_i are the Wilson coefficients and O_i represent the effective operators

3 $b \to s\ell\ell$: lepton universality

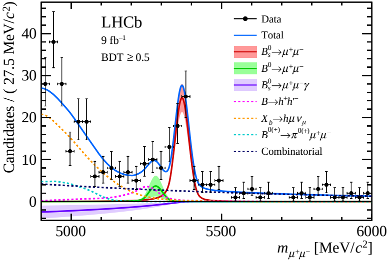
- Branching fractions: $B \to K^*\mu\mu$, $B \to K^+\mu\mu$, $B_s \to \phi\mu\mu$
- Angular analyses define observables with smaller theoretical uncertainties: $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$, $B \to K^*ee$, $\Lambda_b \to \Lambda\mu\mu$
- Test the lepton universality concept via the ratios

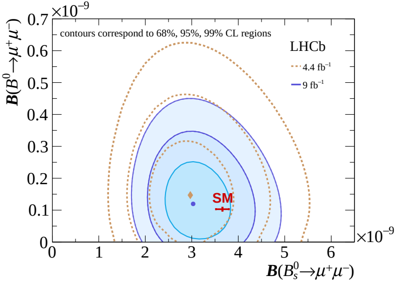


$$R(K^{(*)}) = \frac{B(B \to K^{(*)}\mu\mu)}{B(B \to K^{(*)}ee)}$$

- Different q^2 regions probe different processes in the EFT framework

3 $B_s \to \mu\mu$

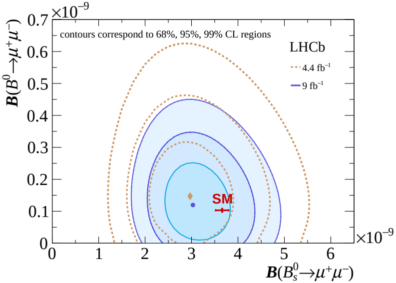


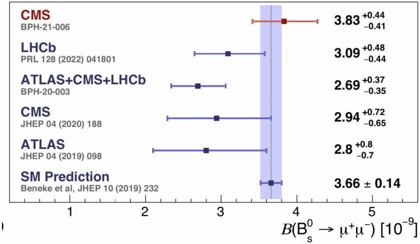


- Suppressed in the SM
- Dominant backgrounds: combinatorial (BDT used for separation) and misidentified hadrons and as muons or partially reconstructed muons
- LHCb measurement: $B(B_s \to \mu\mu) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$ $B(B^0 \to \mu\mu) = (1.2^{+0.8}_{-0.7} \pm 0.1) \times 10^{-10}$
- Result is in agreement with the SM

PRL 128, 041801 PRD 105, 012010

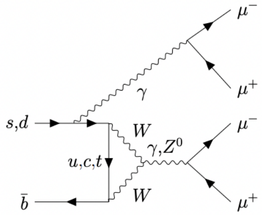
3 $B_s \to \mu\mu$



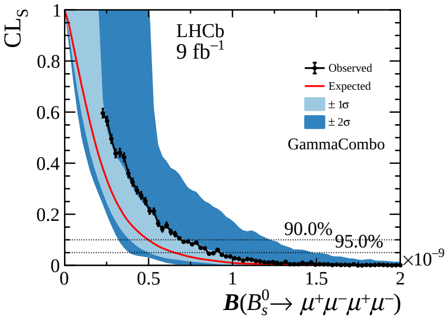


- LHCb measurement:
  $B(B_s \to \mu\mu) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$
  $B(B^0 \to \mu\mu) = (1.2^{+0.8}_{-0.7} \pm 0.1) \times 10^{-10}$
  PRL 128, 041801 · PRD 105, 012010
- Recent CMS measurement:
  $B(B_s \to \mu\mu) = (3.83^{+0.38}_{-0.36}(stat)^{+0.19}_{-0.16}(syst)^{+0.14}_{-0.13} f_s/f_u) \times 10^{-9}$ $B(B^0 \to \mu\mu) = (0.37^{+0.75+0.08}_{-0.67-0.09}) \times 10^{-10}$
  CMS-PAS-BPH-21-006
- Average moves towards SM

3 $B_s \to \mu^+\mu^-\mu^+\mu^-$



- Predicted SM branching fractions: $B(B_s \to 4\mu) \sim 10^{-10}$ $B(B^0 \to 4\mu) \sim 10^{-12}$
- BSM particles can enhance these decays
- Search performed for two light scalars with m ~ 1 GeV

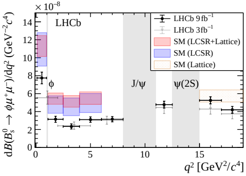


- No evidence for the decays searched is found
- Upper limits at 95% confidence level on their branching fractions set: 1.8×10^{-10} to 2.6×10^{-9}

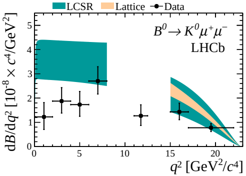
▸ JHEP (2022) 109

3 Branching fractions

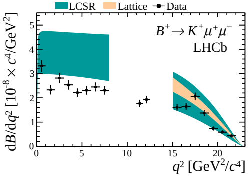
▸ PRL 127, 151801



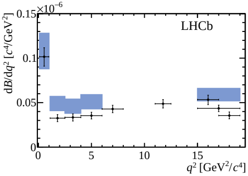
▸ JHEP 06 (2016) 133



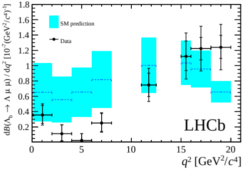
▸ JHEP 06 (2016) 133



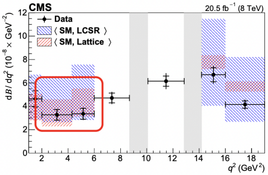
▸ JHEP 11 (2016) 047



▸ JHEP 06 (2015) 115

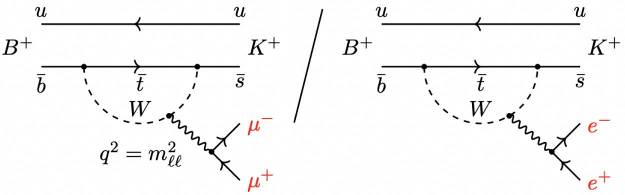


▸ PLB 753 (2016) 424



- Branching fractions are consistently below the SM (at low q^2)
- Tension of 1-3 σ
- Sizeable hadronic uncertainties uncertainties from SM

3 $R(K)$

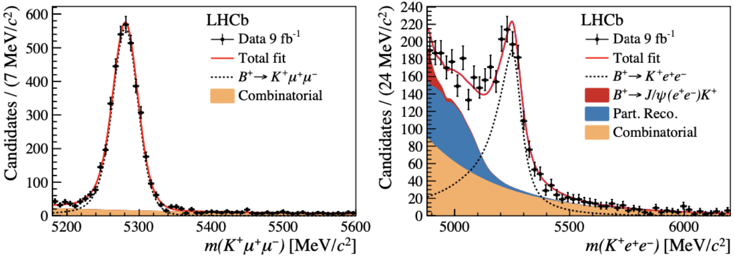


- Test of LFU with the ratio $R_K = \frac{B(B^+ \to K^+ \mu^+ \mu^-)}{B(B^+ \to K^+ e^+ e^-)}$
- The SM prediction is unity
- Analysis strategy: construct double ratio of rare modes $B \to K \ell^+ \ell^-$ and resonant modes $B \to K J/\psi(\to \ell^+ \ell^-)$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(B \to K^{(*)} J/\psi\,(\mu^+ \mu^-))} \Bigg/ \frac{\mathcal{B}(B \to K^{(*)} e^+ e^-)}{\mathcal{B}(B \to K^{(*)} J/\psi\,(e^+ e^-))}$$

- Crosschecks: $r(J/\psi) = 1$ and $r(\psi(2S)) = 1$

3 $R(K)$: experimental challenges

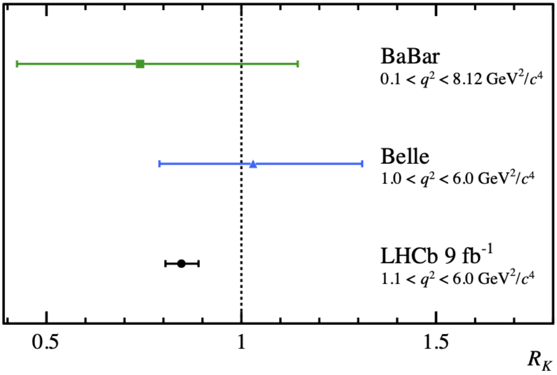


- LHCb signals for $B \to K^+\ell^+\ell^-$ (left) and $B \to K^+e^+e^-$
- Main differences due to bremsstrahlung:
  - Worse mass resolution
  - Lower reconstruction and selection efficiency
  - PID and trigger effects

Challenge to control the efficiency due to these effects

Nat. Phys. 18, (2022) 277-282

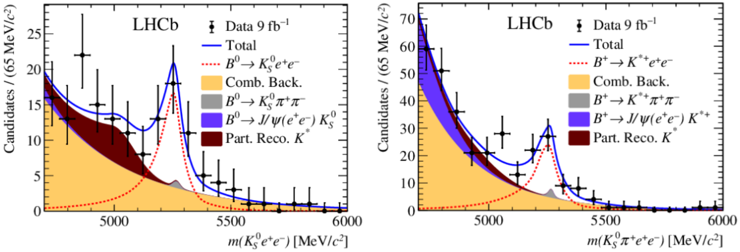
3 $R(K)$: result



▸ Nat. Phys. 18, (2022) 277-282

- Measured $R(K) = 0.846^{+0.042+0.013}_{-0.039-0.012}$ in range $1 < q^2 < 6$ GeV^2
- Tension of 3.1 with the SM

3 $R(K^*)$ with K_s



- Measure $R(K^{(*)})$ with $B \to K_s^0 \ell\ell$ and $B \to K^{*+}(\to K_s^0 \pi^+)\ell\ell$

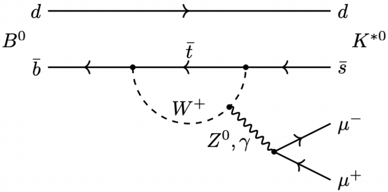
$$R(K_S^0) = 0.66 \, ^{+0.20}_{-0.14} \, ^{+0.02}_{-0.04}$$
$$R(K^{*+}) = 0.70 \, ^{+0.18}_{-0.13} \, ^{+0.03}_{-0.04}$$

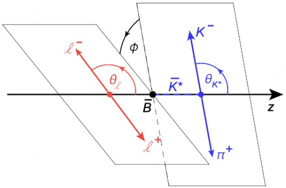
- Each measurement with tension of ~ 1.5 σ with the SM ▸ PRL 128, 191802

What's next:

- Unified analysis of $R(K)$ and $R(K^*)$ → high priority for LHCb
- In addition: R_{pK}, R_ϕ

3 Angular analysis: $B^0 \to K^{*0}\mu\mu$



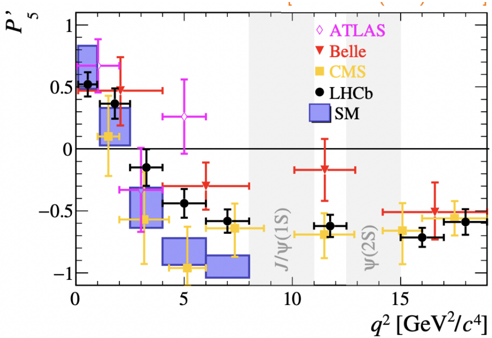


- Three angles feature the decay: θ_l, θ_K, ϕ
- Angular observables sensitive to New Physics: F_L, A_{FB}, S_i

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

3 Angular analysis: $B^0 \to K^{*0}\mu\mu$

- $P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$ → observables where form factors cancel out



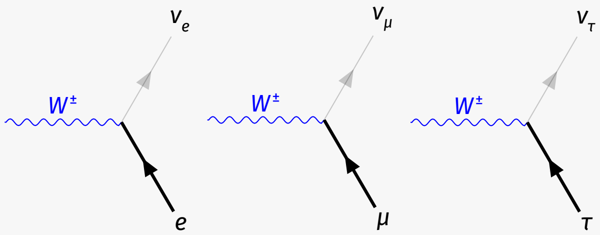
- 2.5 σ to 2.9 σ tension in q^2 [4.0 - 6.0] and [6.0 - 8.0] GeV^2
- LHCb measurements consistent with ATLAS, CMS and Belle

2107.04822 | LHCb, PRL 125 (2020) 011802 | CMS, PLB 781 (2018) 517 | ATLAS, JHEP 10 (2018) 047 | Belle, PRL 118 (2017) 111801

4 Semileptonic B decays

Semileptonic b-hadron decays provide powerful probes for testing the Standard Model(SM) and search for BSM effects

Lepton Flavour Universality (LFU) hypothesis: equal gauge bosons couplings to leptons



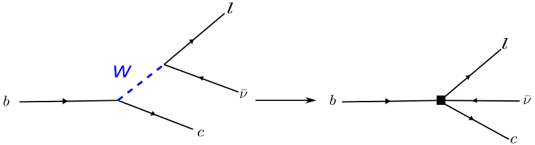
- Description with a tree level diagram in the SM

4 New Physics

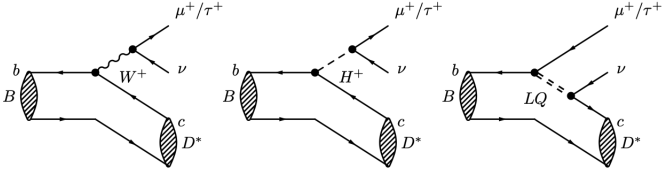
- We can use operators with unknown coupling constants and write them in an effective Hamiltonian

$$H_{eff} = \frac{G_F}{\sqrt{2}} V_{cb} \sum C_i O_i$$

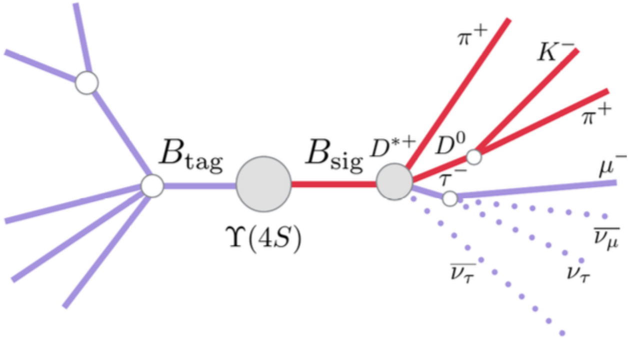
$$C_i = C_i^{SM} + C_i^{NP}$$



- C_i^{NP} are the Wilson coefficients that describe the NP effects
- O_i are effective operators that can be of a vector, scalar or tensor type



Experimental challenge

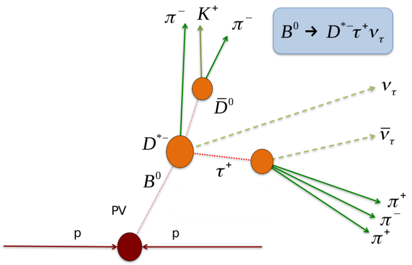


- Difficulty: two neutrinos for $\tau \to \pi\pi\nu_\tau$ and 2 neutrinos for $\tau \to \mu\nu_\mu\nu_\tau$
- Main backgrounds: $B \to D^*\mu\nu$, $B \to D^{**}\mu\nu$, $B \to D^*DX$, $B \to D^*DX$, $B \to D^*\pi\pi\pi X$, combinatorial and misidentified backgrounds
- Can make precise measurements at LHCb and B factories

- Ratios of branching fractions is one choice to test LFU

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

- τ decay modes used: $\tau^- \to \mu^- \nu_\mu \nu_\tau$ and $\tau^- \to \pi^+ \pi^- \pi^- \nu_\tau$



$R(D^*)$ with $\tau \to \mu\nu\nu$
2.1 σ greater than the SM expectation: 0.252 ± 0.003

$R(D^*)$ with $\tau \to \pi\pi\pi\nu$
1 σ higher than the SM prediction

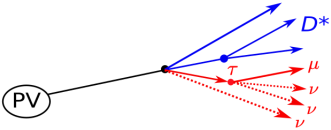
PRL 120, 171802 PRL 115 111803

NEW: Simultaneous $R(D) - R(D^*)$ measurement

Any discrepancy could be a clear sign of New Physics (NP)

4 Simultaneous $R(D)$-$R(D^*)$ at LHCb

- First joint measurement of $R(D) - R(D^*)$: LHCb-PAPER-2022-039 in preparation



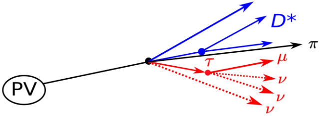
$$R(D^*) = \frac{B(B \to D^* \tau \nu)}{B(B \to D^* \mu \nu)}$$

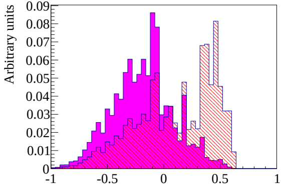
- Discriminating kinematic variables are:
  - the muon energy E_μ
  - $m^2_{miss} = (p_B - p_{D^*} - p_l)^2$
  - $q^2 = (p_B - p_{D^*})^2$

- B momentum approximated with the relation:

$$(p_B)_z = \frac{m_B}{m_{reco}} (p_{reco})_z$$

- Isolation: reject backgrounds with additional charged tracks





Main background contributions:

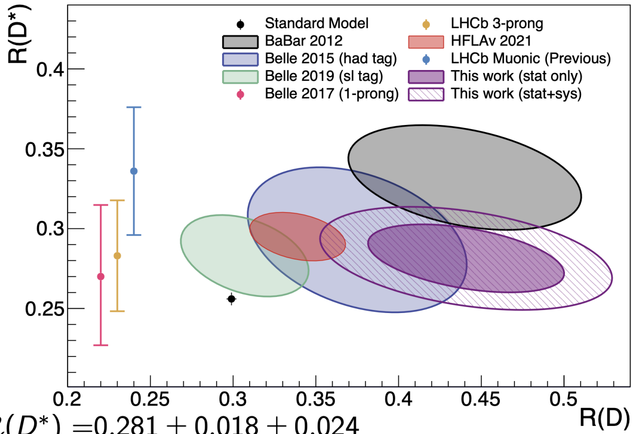
- $B \to D^{**}\mu\nu$
- $B_s \to D_s\mu\nu$
- Semileptonic decays to heavier charmed hadrons decaying to $D^{**} \to D^{*+}\pi\pi$
- $B \to D^{**}\tau\nu$
- $B \to D^{*+}H_cX$
- Hadrons(π, K, p) misidentified as muons
- Combinatorial backgrounds - wrong-sign final state combinations

Fitting strategy:

- Signal region + 3 control samples, for both D^0 and D^{*+} samples
- Simultaneous fit with three dimensional templates that extracts the relative contributions of signal and normalization modes and their form factors
- Improvements from previous LHCb measurement: detailed study of the backgrounds and completely new procedure of understanding the calibration of simulation to match data

4 Simultaneous $R(D^0)$-$R(D^*)$ at LHCb

Result:

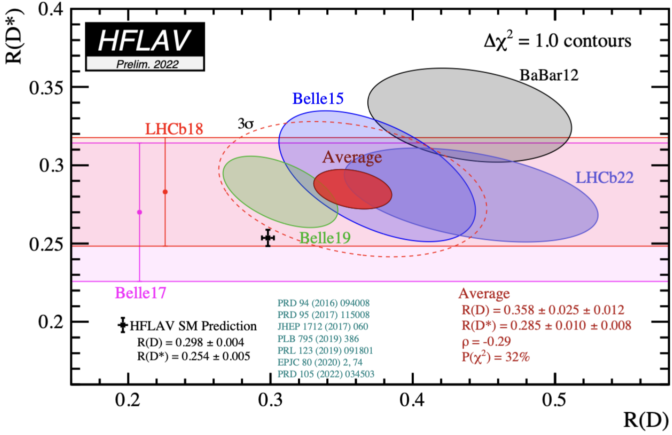


$\mathcal{R}(D^*) = 0.281 \pm 0.018 \pm 0.024$

$\mathcal{R}(D) = 0.441 \pm 0.060 \pm 0.066$

- 1.9σ agreement with the SM

4 The big picture



- New average: change from 3.3σ to 3.2σ
- Overall agreement between measurements
- Next: Angular analyses give more information on sensitivity to New Physics → ongoing measurement

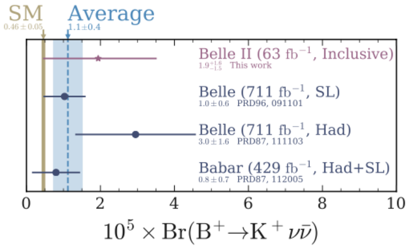
4 Belle II status and prospects

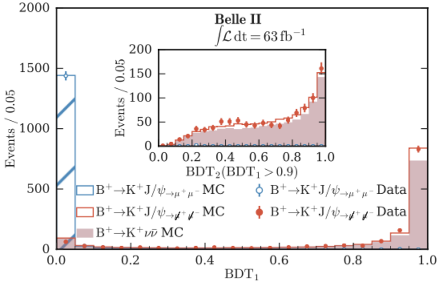
Observable	Current Belle/ Babar	2019 LHCb	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
CKM precision, new physics in CP Violation				
$\sin 2\beta/\varphi_1$ ($B\to J/\psi K_S$)	0.03	0.04	0.012	0.005
γ/φ_3	13°	5.4°	4.7°	1.5°
α/φ_2	4°	–	2	0.6°
$\lvert V_{ub}\rvert$ (Belle) or $\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ (LHCb)	4.5%	6%	2%	1%
φ_s	–	49 mrad	–	–
$S_{CP}(B\to\eta' K_S$, gluonic penguin)	0.08	○	0.03	0.015
$A_{CP}(B\to K_S\pi^0)$	0.15	–	0.07	0.04
New physics in radiative & EW Penguins, LFUV				
$S_{CP}(B_d\to K^*\gamma)$	0.32	○	0.11	0.035
$R(B\to K^*l^+l^-)$ ($1<q^2<6$ GeV$^2/c^2$)	0.24	0.1	0.09	0.03
$R(B\to D^*\tau\nu)$	6%	10%	3%	1.5%
$Br(B\to\tau\nu)$, $Br(B\to K^*\nu\nu)$	24%, –	–	9%, 25%	4%, 9%
$Br(B_d\to\mu\mu)$	–	90%	–	–
Charm and τ				
$\Delta A_{CP}(KK-\pi\pi)$	–	8.5×10^{-4}	–	5.4×10^{-4}
$A_{CP}(D\to\pi^+\pi^0)$	1.2%	–	0.5%	0.2%
$Br(\tau\to e\gamma)$	$<120\times10^{-9}$	–	$<40\times10^{-9}$	$<12\times10^{-9}$
$Br(\tau\to\mu\mu\mu)$	$<21\times10^{-9}$	$<46\times10^{-9}$	$<3\times10^{-9}$	$<3\times10^{-9}$

▸ Belle II Physics book

- Belle results and prospects presented today by ▸ Racha Cheaib

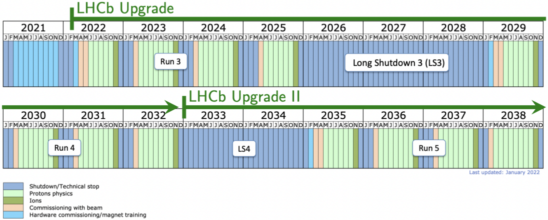
Belle II: $B \to K\nu\nu$





- One of the first flavour publications with Belle II: ‣ PRL 127 181802 (2021)
- Upper limit on the branching fraction of $B^+ \to K^+\nu\nu$
- Improved analysis methods: using properties of other B meson in the $B\bar{B}$ event

4 Where do we stand



	Integrated luminosity $[\text{fb}^{-1}]$	
	LHCb	ATLAS/CMS
Run 1	3	25
Run 2	9	+140
Run 3	23	+300
Run 4	50	+300/year
Run 5(+)	300	+300/year

- Updates of flavour anomaly measurements with full Run 1 + Run 2 are ongoing
- Run 3 already started at LHCb: commissioning a brand new detector has a lot of challenges ▸ LHCb Upgrade
- Important complementary results from Belle II to come
- HL-LHC: expecting even better precision of measurements

observable	LHCb 2025	Belle II	LHCb Upgrade II
$R(D^*)$	0.0072	0.005	0.002
$R(J/\psi)$	0.071	-	0.02
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	34%	-	10%
$R_K(1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.025	0.036	0.007
$R_{K^*}(1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.031	0.032	0.008

5 Outline

5 Summary

- Rare B and semileptonic decays are an excellent test bench for New Physics effects
- Limited number of measurements up to now, but updates in preparation
- The LHC Run 3 data has potential to distentangle the tensions
- LHCb, Belle II, ATLAS and CMS have a lot to say in near future
- Still: flavour physics remains exciting to follow

Thank you!

BACKUP SLIDES

6 Full angular distribution $B \to D^* l\nu$

$$\frac{d^4\Gamma}{dq^2 dcos\theta_l dcos\theta_d d\chi} = \frac{3G_F^2|V_{cb}|^2}{256(2\pi)^4 m_B^3}\, q^2\, (1 - \frac{m_l^2}{q^2})\sqrt{\lambda_{D^*}} \times B(D^* \to D\pi) \times \Big\{$$

$$(|H_+|^2 + |H_+|^2)\left(1 + cos^2\theta_l + \frac{m_l^2}{q^2}\, sin^2\theta_l\right) sin^2\theta_D + 2\, [|H_+|^2 - |H_-|^2]\, cos\theta_l\, sin^2\theta_D +$$

$$+4|H_0|^2 \left(sin^2\theta_l + \frac{m_l^2}{q^2}\, cos^2\theta_l\right) cos^2\theta_D + 4\, |H_t|^2\, \frac{m_l^2}{q^2}\, cos^2\theta_D -$$

$$-2\, \beta_l^2\, (Re[H_+H_-^*]\, cos2\chi + Im[H_+H_0^* - H_-H_0^*]\, sin2\chi)\, sin^2\theta_l\, sin^2\theta_D -$$

$$-\beta_l^2\, (Re[H_+H_0^* + H_-H_0^*]\, cos\chi; -Im[H_+H_0^* + H_-H_0^*]\, sin\chi); sin2\theta_l\, sin2\theta_D -$$

$$-Re[H_+H_0^* - H_-H_0^* - \frac{m_l^2}{q^2}(H_+H_t^* + H_-H_t^*)]\, cos\chi\, sin\theta_l\, sin2\theta_D -$$

$$-2Im[H_+H_0^* + H_-H_0^* - \frac{m_l^2}{q^2}(H_+H_t^* + H_-H_t^*)]\, sin\chi\, sin\theta_l\, sin2\theta_D +$$

$$+8Re[H_0H_t^*]\, \frac{m_l^2}{q^2}\, cos\theta_l\, cos^2\theta_D \Big\}, \beta_l(q^2) = \sqrt{1 - \frac{m_l^2}{q^2}},\; H(q^2) = \tilde{\epsilon}^{\mu *} \langle D^*(\epsilon)|J_\mu|\bar{B}\rangle$$