Measurements of lepton flavour universality at the LHC

HQL 2025 – Beijing

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Lepton Flavour Universality (LFU)

Accidental global flavour symmetries in the SM:

- Conservation of Lepton Number (L) & **Lepton Flavour Universality (LFU)**
- Though Yukawa coupling **flavour-specific**
  - $\rightarrow$ Equal coupling of EW gauge bosons to charged leptons (up to mass differences).
  - $\rightarrow$ Arises due to smallness of Yukawa terms w.r.t. weak coupling constants: $\frac{\sqrt{2m_l}}{\langle v \rangle} \sim \mathcal{O}(10^{-2} - 10^{-6}) \ll g, g'$
- Being a fundamental axiom of the SM, LFU acts as a good probe of BSM processes.

LFU already well established in $W^{\pm}/Z$ decays:

$$\frac{Z^0 \rightarrow \mu^+\mu^-}{Z^0 \rightarrow e^+e^-} = 1.0009 \pm 0.0028$$

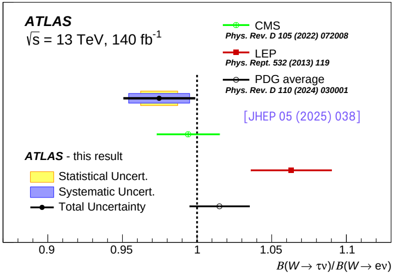
[Phys.Rept. 427 (2006) 257]

$$\frac{Z^0 \rightarrow \tau^+\tau^-}{Z^0 \rightarrow e^+e^-} = 1.0019 \pm 0.0032$$

$$\frac{W^{\pm} \rightarrow \tau^{\pm}\nu_{\tau}}{W^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}} = 0.992 \pm 0.013$$

[Nature Physics 17, 813 (2021)]

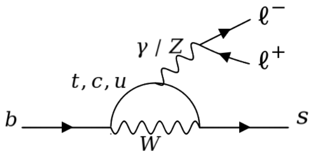
$$\frac{W^{\pm} \rightarrow \tau^{\pm}\nu_{\tau}}{W^{\pm} \rightarrow e^{\pm}\nu_{e}} = 0.975 \pm 0.012 \pm 0.020$$



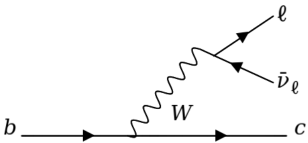
Recent efforts to test LFU in EW boson decays !

Testing LFU at the LHC

General idea across all experiments:
Compare observable in a given process for different lepton flavours



- Flavour-changing neutral current (FCNC).
- Loop-induced and CKM suppressed in SM.
- BF $\sim 10^{-6} - 10^{-7}$.
- Potential NP contributions of same size as SM.
- Fully reconstructible final state.

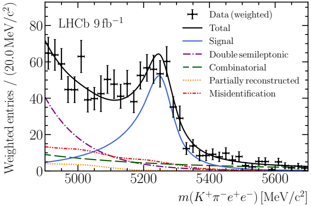


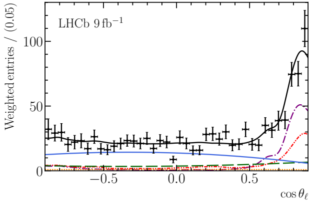
- Flavour-changing charged current (FCCC).
- CKM favoured in SM.
- BF $\sim 10^{-2} - 10^{-1}$.
- Neutrinos in final state.
- τ decays accessible: probe 3rd lepton generation NP couplings.

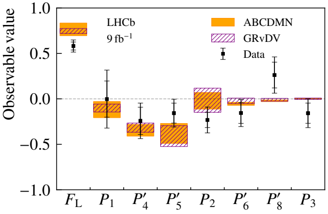
Here focusing on b-hadrons decays: **heavy** and **long-lived**

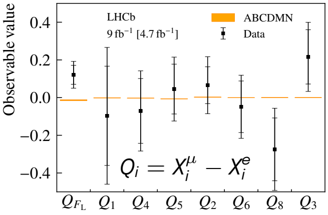
Angular analysis of $B^0 \to K^{*0} e^+ e^-$

- $B^0 \to K^{*0} \ell^+ \ell^-$ decay previously studied in the $K^{*0} \mu^+ \mu^-$ channel, show some tension in P_5' angular observable.
- Analyses with $e^\pm$ complicated by experimental factors (Bremsstrahlung, calorimeter resolution, etc..).
- **First angular analysis** for $b \to s e^+ e^-$ in LHCb with 9fb^{-1} in central q^2 region $\Rightarrow q^2 \in [1.1, 6]\text{GeV}^2/c^4$.
- Observables extracted in **4D unbinned ML fit** to $\left(m(K^- \pi^+ e^+ e^-), \cos\theta_\ell, \cos\theta_K, \phi\right)$.
- Results in **good agreement** with SM and $B^0 \to K^{*0} \mu^+ \mu^-$









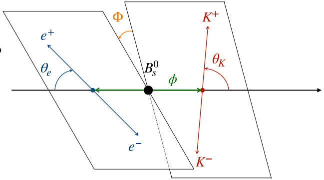
[JHEP 2506 (2025) 140]

Angular analysis of $B_s^0 \to \phi e^+ e^-$

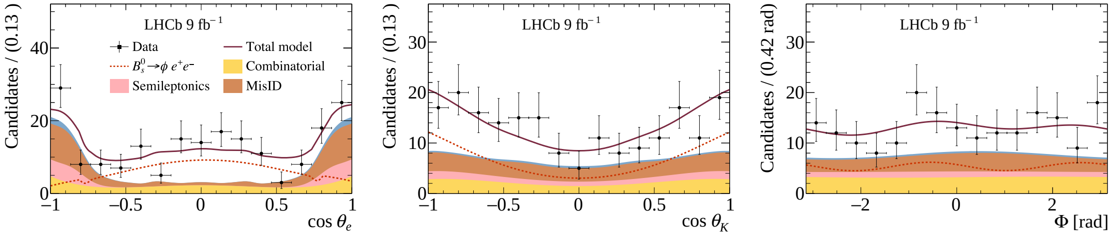
- Run1 + Run2 dataset (9fb^{-1}) $\Rightarrow$ limited sample size.
- Focus on integrated over decay-time, CP-averaged differential decay rate projections.
- **First measurement** of the angular observables F_L, S_3, A_6 and A_9 in **low, central and high** q^2 bins: $[0, 1.1]$, $[1.1, 6]$ and $[15, 19]$ GeV^2/c^4.

$$\frac{d^3(\Gamma+\bar{\Gamma})}{dq^2\, d\cos\theta_K\, d\cos\theta_e} \propto \frac{3}{4}(1-F_L)\sin^2\theta_K\left(1+\frac{1}{3}\cos 2\theta_e\right) + F_L\cos^2\theta_K(1-\cos 2\theta_e) + \frac{4}{3}A_6\sin^2\theta_K\cos\theta_e$$

$$\frac{d^2(\Gamma+\bar{\Gamma})}{dq^2\, d\Phi} \propto 1 + S_3\cos 2\Phi + A_9\sin 2\Phi$$

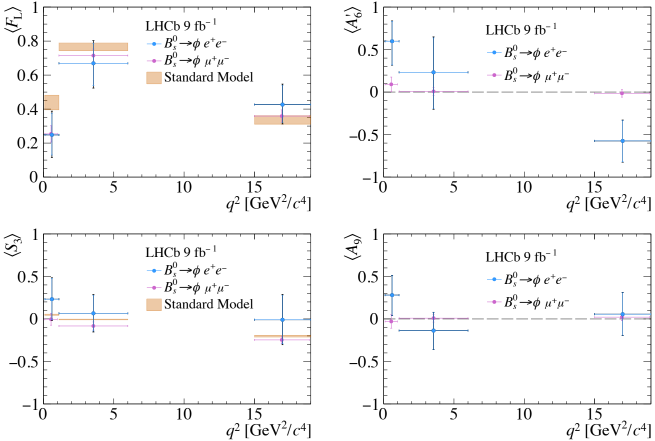


[JHEP 07 (2025) 069]



Angular analysis of $B_s^0 \to \phi e^+ e^-$

- Results statistically limited ($\epsilon_{stat} \sim 2 - 4 \times \epsilon_{syst}$).
- Largest sources of syst. uncertainty are the models for the mass and angular distributions of the backgrounds (limited by available control/simulation sample sizes).
- Results **Compatible with SM** and with previous $B_s^0 \to \phi\mu^+\mu^-$ analysis.
- **Additional analysis** at verly low q^2 provides additional angular measurements.



[JHEP 07 (2025) 069]

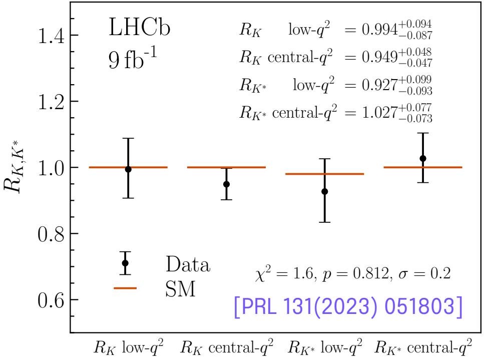
LFU tests in R_H observables

For $b \to s\ell\ell$ transitions, define R_H as:

$$\mathbf{R_H} = \frac{\int \frac{d\mathcal{B}(\mathbf{B}\to\mathbf{H_s}\mu^+\mu^-)}{\mathbf{dq^2}}\mathbf{dq^2}}{\int \frac{d\mathcal{B}(\mathbf{B}\to\mathbf{H_s e^+e^-})}{\mathbf{dq^2}}\mathbf{dq^2}} \equiv \mathbf{1} \pm \mathcal{O}(\mathbf{10^{-2}}) \pm \mathcal{O}(\mathbf{10^{-3}})$$

$$= \frac{\mathbf{N(B \to H_s}\mu^+\mu^-)}{\mathbf{N(B \to H_s e^+ e-)}} \cdot \frac{\epsilon(\mathbf{B \to H_s e^+ e^-})}{\epsilon(\mathbf{B \to H_s}\mu^+\mu^-)}$$

$$\times \frac{\mathbf{N(B \to H_s J/\ (ee))}}{\mathbf{N(B \to H_s J/\ (}\mu\mu))} \cdot \frac{\epsilon(\mathbf{B \to H_s J/\ (}\mu\mu))}{\epsilon(\mathbf{B \to H_s J/\ (ee))}}$$

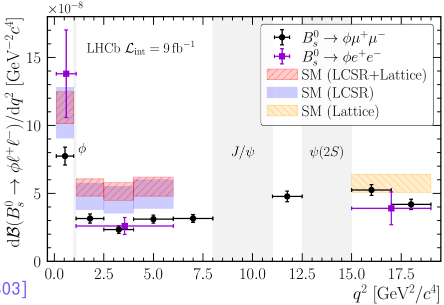


$\Rightarrow$ The value of R_H is expected to be very close to 1 (μ/e ratios).

- Recent $R_{K(*)}$ updates from LHCb in **agreement with SM**.
- Still interesting to test LFU in these observables: ”cleaner” than angular observables, reducing uncertainties will yield more conclusive results

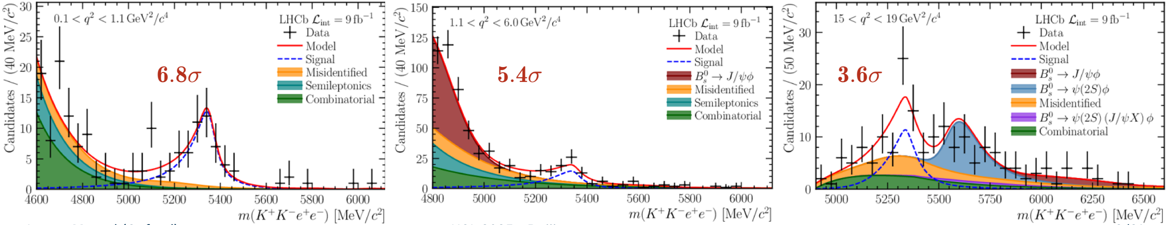
LFU tests in $B_s^0 \to \phi \ell^+ \ell^-$

- **First LFU test** in B_s decays and **first measurement** of $\mathcal{B}(B_s^0 \to \phi e^+ e^-)$.
- Measurement in **low, central and high** q^2 bins: $[0.1, 1.1]$, $[1.1, 6]$ and $[15, 19]$ GeV^2/c^4.
- Normalized w.r.t. $B_s^0 \to \phi J/\Psi(\ell\ell)$
- Results **compatible with SM**, uncertainty on R_ϕ^{-1} statistically dominated.



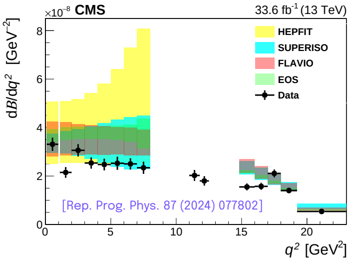
q^2 [GeV$^2/c^4$]	R_ϕ^{-1}
$0.1 < q^2 < 1.1$	$1.57^{+0.28}_{-0.25} \pm 0.05$
$1.1 < q^2 < 6.0$	$0.91^{+0.20}_{-0.19} \pm 0.05$
$15.0 < q^2 < 19.0$	$0.85^{+0.24}_{-0.23} \pm 0.10$

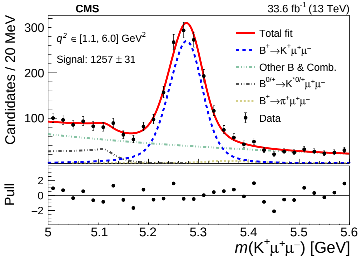
[PRL 134 (2025) 121803]

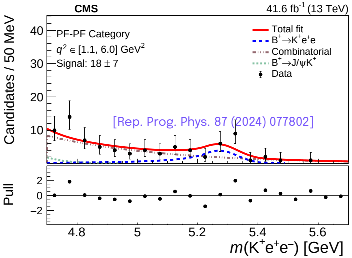


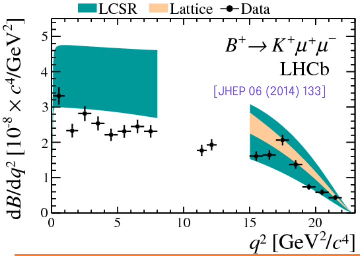
R_K and measurement of $\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$

- First $b \to s\ell\ell$ LFU measurement in CMS with Run2 dataset.
- Use of novel trigger stategy: **b-parking** to record 41.6fb^{-1} of data in 2018.
- Trigger strategy differs for μ and e channels to ensure large $B^+ \to K^+\mu^+\mu^-$ dataset
  $\Rightarrow$ no cancellation of ϵ_{trig} in ratio computation.
- Signal extracted from fit to $m(K^+\ell^+\ell^-)$.









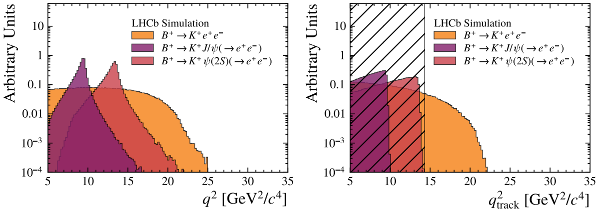
$R_K[1.1, 6]\text{GeV}^2/c^4 = 0.78^{+0.46}_{-0.23}(\text{stat.})^{+0.09}_{-0.05}(\text{syst.})$ **agrees** with **SM** and:
$R_K[1.1, 6]\text{GeV}^2/c^4 = 0.949^{+0.042}_{-0.041}(\text{stat.})^{+0.022}_{-0.022}(\text{syst.})$ from **LHCb**

Measurement of $\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$
Excellent agreement CMS/LHCb.
Both **lower** than SM expectation.

R_K at high q^2

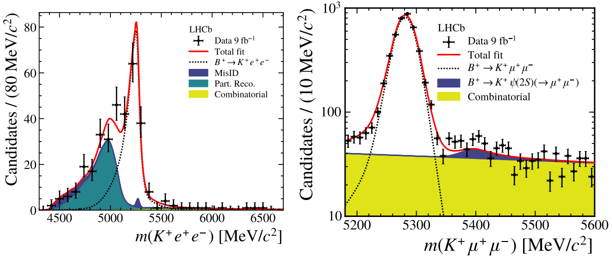
- **First measurement** of R_K in high-q^2 bin ($> 14.3\text{GeV}^2/c^4$) with 9fb^{-1} dataset.
- Use only momenta for q^2_{track} for electrons, not including bremsstrahlung photons.
- Significantly reduces of resonant leakages and misID backgrounds.
- Precise description of shape distortion induced by q^2 requirement .
- LFU result in good agreement with SM:

[JHEP07(2025)198]



$$\mathbf{R_K(q^2 > 14.3GeV^2/c^4) = 1.08^{+0.11+0.04}_{-0.09-0.04}}$$

- Uncertainty statistically dominated.
- Leading systematics from partially reconstructed and misidentified backgrounds.



More rare decays @ LHCb in Thomas' talk

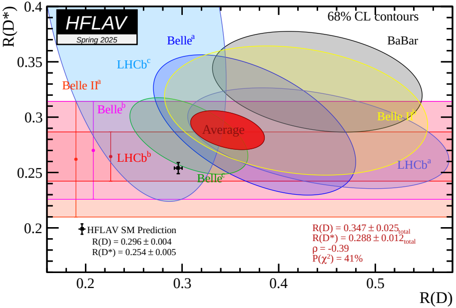
LFU tests in $b \to c\ell\bar{\nu}_\ell$

- LFU tests from $R(H_c)$ ratios defined as:

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c\tau^+\bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c\mu^+\bar{\nu}_\mu)}$$

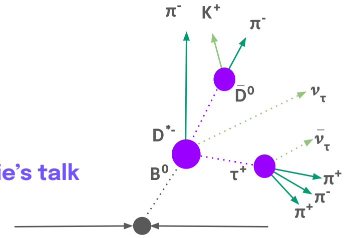
with $H_b = B^0, B_s^0, B_{(c)}^+, \Lambda_b^0$ and $H_c = D^*, D^{0/+}, D_s, J/\Psi, \Lambda$

- Various $R(D^{(*)})$ results from different experiment deviations with a total significance of $\sim \mathbf{3.3\sigma}$.
- Experimental challenges: partially reconstructed numerous backgrounds.

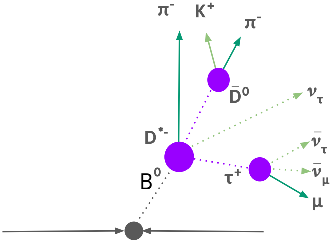


Two decay topologies usually considered:

Hadronic τ: $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$



Muonic τ: $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$



More in Jie's talk

$R(D^+)$ and $R(D^{*+})$ with muonic τ decays

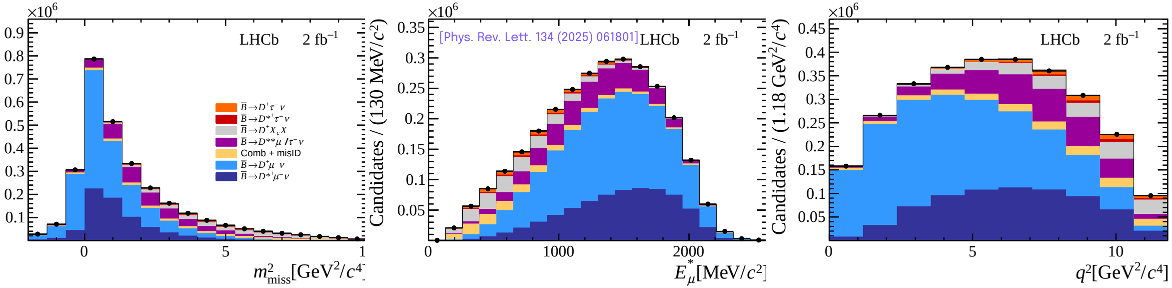
- 2015/2016 dataset (2fb^{-1}).
- **Simultaneous measurement** of $R(D^+)$ and $R(D^{*+})$ with muonic τ decays:

$$\mathrm{R}(\mathrm{D}^{(*)+}) = \frac{N(B^0 \to D^{(*)+}\tau^-\nu_\tau)}{N(B^0 \to D^{(*)+}\mu^-\nu_\mu)} \cdot \frac{\epsilon(B^0 \to D^{(*)+}\mu^-\nu_\mu)}{\epsilon(B^0 \to D^{(*)+}\tau^-\nu_\tau)} \cdot \frac{1}{\mathcal{B}(\tau^- \to \mu^-\nu_\mu\nu_\tau)}$$

and $D^+ \to K^-\pi^+\pi^+$, $D^{*+} \to D^+\pi^0$

Signal yields extracted from 3D template fits to $(q^2, E^*_\mu, m^2_{miss})$, with:

- $q^2 = (p_B - p_{D^{(*)}})^2$
- E^*_μ = muon E in B rest frame
- $m^2_{miss} = (p_B - p_{D^{(*)}} - p_\mu)^2$



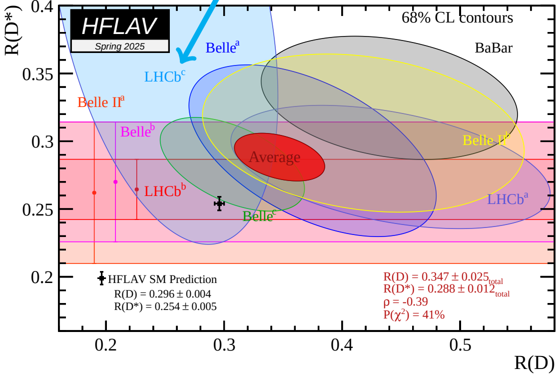
$R(D^+)$ and $R(D^{*+})$ with muonic τ decays

- Results limited by systematic uncertainties (led by form factor parametrisation and background modelling).
- Results are in agreement with previous ones.

Source	$R(D^+)$	$R(D^{*+})$
Form factors	**0.023**	**0.035**
$B \to D^{**}[D^+X]\mu/\tau\nu$ fractions	**0.024**	**0.025**
$B \to D^+X_cX$ fraction	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	**0.047**	**0.085**
Statistical uncertainty	**0.043**	**0.081**

[Phys. Rev. Lett. 134 (2025) 061801]

$$R(D^-) = 0.249 \pm 0.043 \pm 0.047$$
$$R(D^{*-}) = 0.402 \pm 0.081 \pm 0.085$$



Evidence for $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decays

- Search for $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ (hadronic τ) with full Run1 + Run2 dataset (9fb^{-1}).
- Three BDTs used to reject: fake D^{**0}, multi-body D_s^+ decays and τ-like D_s^+ decays.
- Yields extracted from fit to $m(D^{*+}\pi^-)$.
- 3.5σ significance for $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$: **first evidence** of the decay.

- LFU ratio:

$$\frac{\mathcal{B}(B^- \to D^{**0}_{1,2}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^- \to D^{**0}_{1,2}\mu^-\bar{\nu}_\mu)} = 0.13 \pm 0.04$$

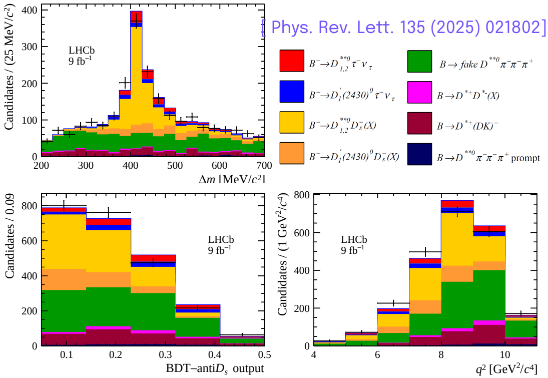
$\Rightarrow$ In agreement with SM predictions.

- Branching ratio measurement:

$$\frac{\mathcal{B}(B^- \to D^{**0}_{1,2}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B^- \to D^{**0}_{1,2}D_s^{(()})} = 0.19 \pm 0.04$$

$\Rightarrow$ Provides useful inputs for other $b \to c\ell\nu$ analyses.

[Phys. Rev. Lett. 135 (2025) 021802]



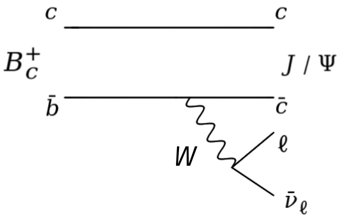
LFU tests with $R(J/\Psi)$ ratios

- Follows the logic of LFU tests $R(H_c)$ ratios, here in B_c^+ decays.
- Previous measurement by LHCb:

$$R(J/\Psi) = 0.71 \pm 0.17 \pm 0.18 \xrightarrow{2\sigma \text{ from}} R(J/\Psi)_{SM} = 0.2582 \pm 0.0038$$

[PhysRevLett.120.121801] [PhysRevLett.125.222003]

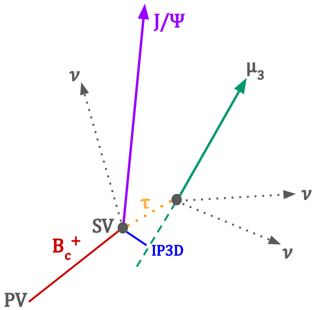
- Run2 results from CMS for **muonic** and **hadronic** τ channels:

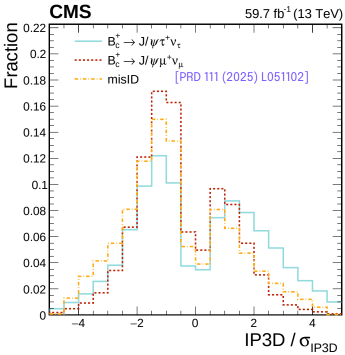


$$R(J/\Psi) = \frac{\mathcal{B}(B_c^+ \to J/\Psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\Psi \mu^+ \nu_\mu)}$$

$R(J/\Psi)$ - Leptonic tau

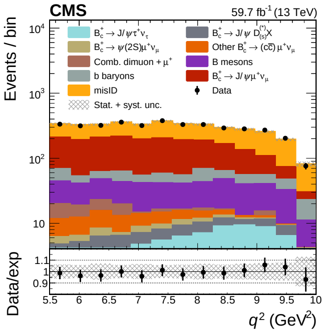
- Run2 data (2018).
- Experimental challenge: same signature for τ and μ channels (three μ) $\Rightarrow$ same reconstruction.
- Separation of τ/μ events using **topological** and **kinematical** variables:
  - $q^2 = (p_B - p_{J/\Psi})^2$
  - 3rd muon impact parameter w.r.t $p_{J/\Psi}$ (IP3D)
  - Secondary vertex displacement L_{xy}
- Largest background contribution from J/Ψ + misID hadron and H_b with $J/\Psi\mu$ final state.

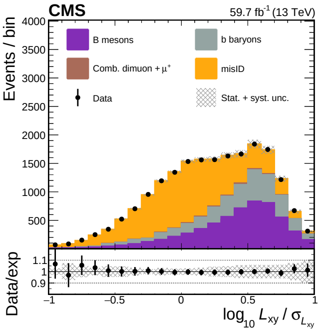




$R(J/\Psi)$ - Leptonic tau

- Events classified in 7 regions of $(q^2, m(3\mu), L_{xy})$, further split in two based on third muon isolation.
- Simultaneous binned ML fit in the **14 regions**.





Contribution	Type	Unc. (10^{-2})
Form factor (theory)	S	19
misID statistical	S (bin-by-bin)	13
misID systematic	N, S	8, 0.7
Finite MC size	S (bin-by-bin)	9
Topological	S	9
Efficiencies	N	6
Total systematic uncertainty		28

[PRD 111 (2025) L051102]

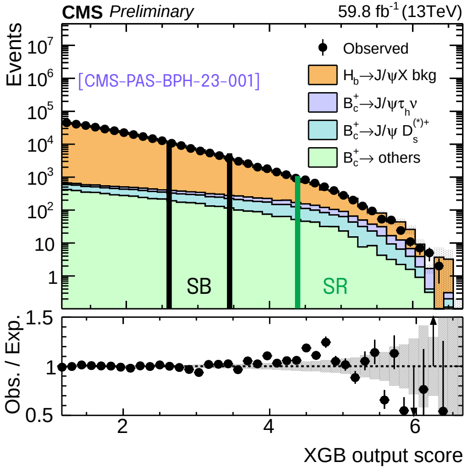
$$R(J/\Psi) = 0.17^{+0.21}_{-0.22}(\text{syst.})^{+0.19}_{-0.18}(\text{th.})^{+0.18}_{-0.17}(\text{stat.})$$

$\Rightarrow$ compatible with SM (0.3σ) and LHCb (1.3σ)

Leading uncertainties come from form factor computation and MisID statistical shape uncertainties

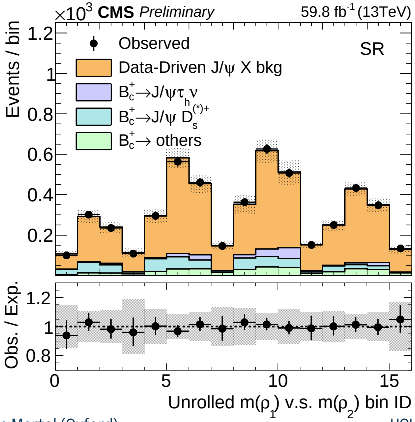
$R(J/\Psi)$ - Hadronic tau

- Full Run2 data (2016, 2017, 2018).
- Different signature for τ and μ channels:
  - τ: muon pair + 3 pions.
  - μ: muon pair + third muon.
- Background contributions from:
  - b-hadrons: $H_b \to J/\Psi X$.
  - $H_b \to D_s^* J/\Psi$.
  - B_c with $c\bar{c} \to J/\Psi$ feed-downs.
- BDT to reduce backgrounds, use τ flight length significance, vertex quality, isolation, etc.. as input.
- Two regions defined based on BDT output:
  - a signal-enriched region (SR) .
  - a sideband background-enriched region (SB).
- SB used to derive the inclusive J/Ψ backgrounds in SR.

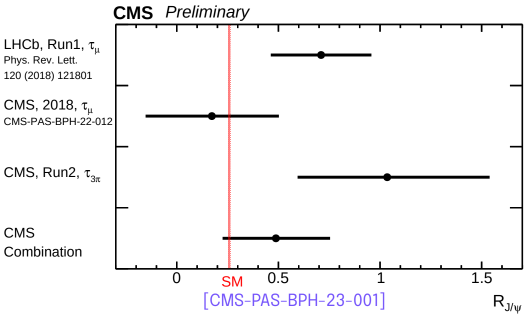


$R(J/\Psi)$ - Hadronic tau

- Fit to intermediate $\rho_0(\pi^+\pi^-)$ mass.
- Two possibilities using three pions from $\tau^+ \to \pi^+\pi^-\pi^+\nu_\tau$.
- Simultaneous binned ML fit to unrolled $(m(\rho_1), m(\rho_2))$ in SB and SR.
- $R(J/\Psi)$ computed with hadronic τ channel, compatible with leptonic τ result. Leptonic + hadronic combined $R(J/\Psi)$ value computed: compatible with previous results and SM.



$$R(J/\Psi)_{3\pi} = 1.04^{+0.50}_{-0.44}$$



[CMS-PAS-BPH-23-001]

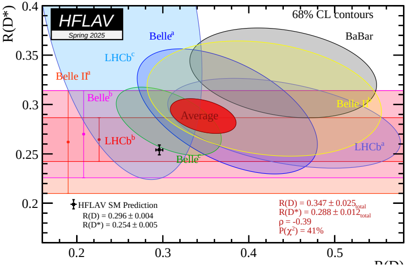
$$R(J/\Psi)_{comb} = 0.49 \pm 0.25(\text{syst.}) \pm 0.09(\text{stat.})$$

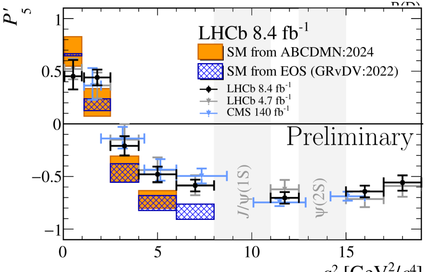
Summary

- LFU tests provide some of the cleanest ways to probe the SM.
- LFU continues to be at the centre of flavour physics programs.
- Continuous effort by LHC experiments allows results to be cross-checked.
- **Good agreement** between results from LHC experiments, mos in agreement with SM.
- Still unresolved **tensions** in FCCC ratios/FCNC angular obs.

The search continues:

- Expansions to additional measurements: LFU tests in rare charm decays, angular analyses in semileptonic B decays...
- Many updates to come with **large datasets** from Run3.
- Results and cross-checks from non-LHC experiments (Belle II, BESIII...)





[LHCb-PAPER-2025-041] (in preparation)

Thank you for your attention !

Backup

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