Tests of lepton flavour universality

Lorenzo Capriotti

on behalf of the LHCb collaboration

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

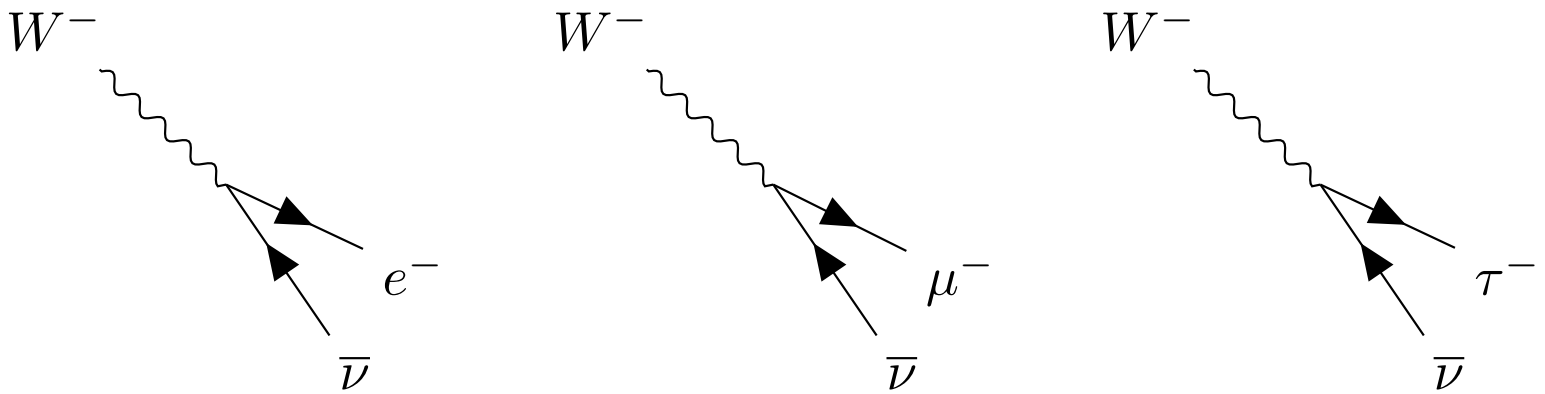
LHC Days, Split
18/09/2018

Lepton couplings in the Standard Model

The requirement of gauge invariance of the Standard Model Lagrangian implies that

- if the electroweak interactions are described by a Yang-Mills theory
- if the symmetry group of the electroweak interactions is $SU(2) \otimes U(1)$

then the lepton couplings are universal

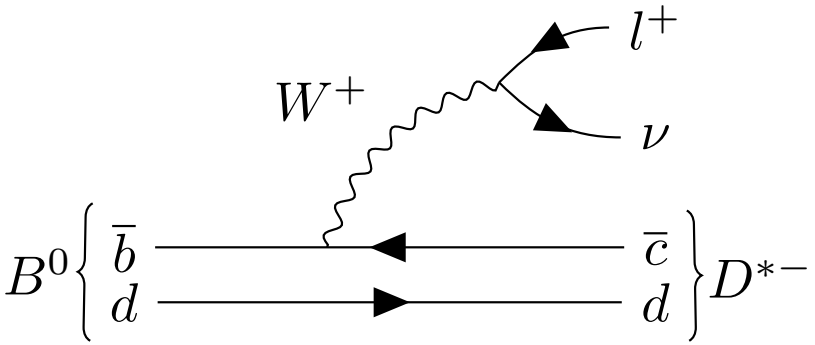


Only difference in amplitudes resides in the different volume of the phase space

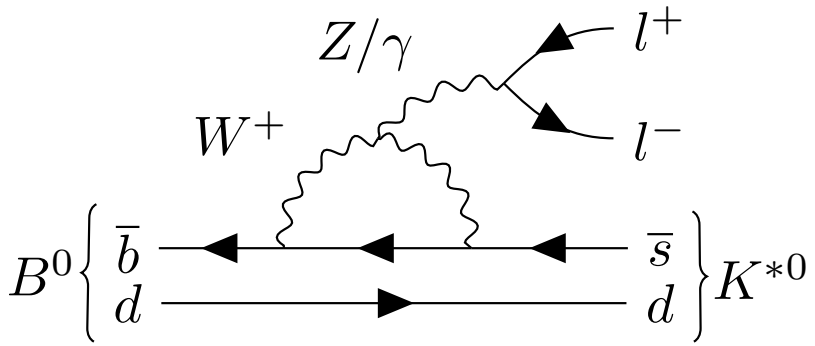
Hints of lepton non-universality

Lepton universality thoroughly tested in direct and indirect measurements

- Several deviations observed by different experiments
- Flavour-changing charged currents: semileptonic B decays



- Flavour-changing neutral currents: rare $b \to sll$ transitions

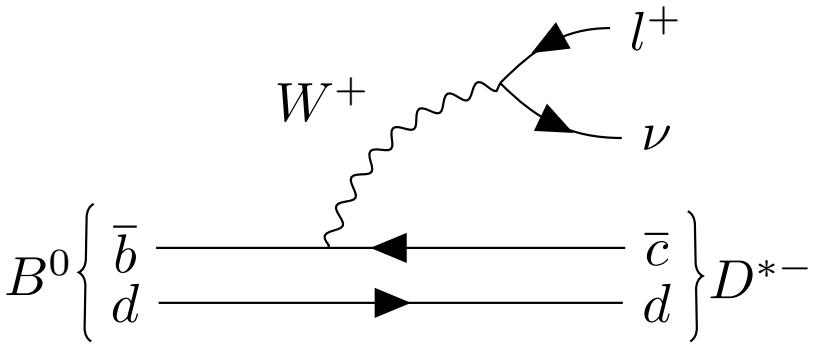


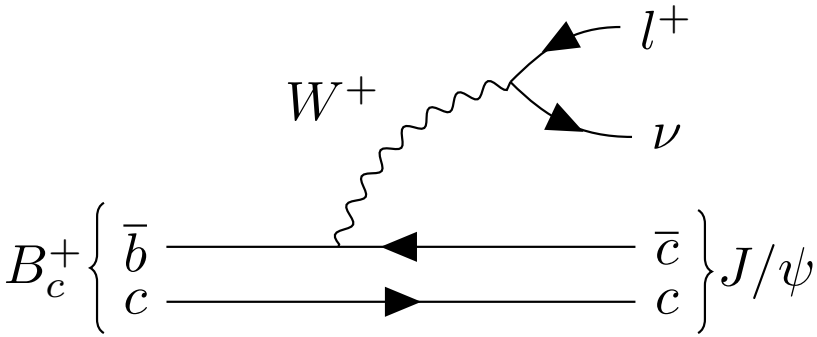
Violation of lepton universality: SM conditions not satisfied, or contribution from a new unpredicted source

LEPTON UNIVERSALITY TESTS WITH FLAVOUR-CHANGING CHARGED CURRENTS

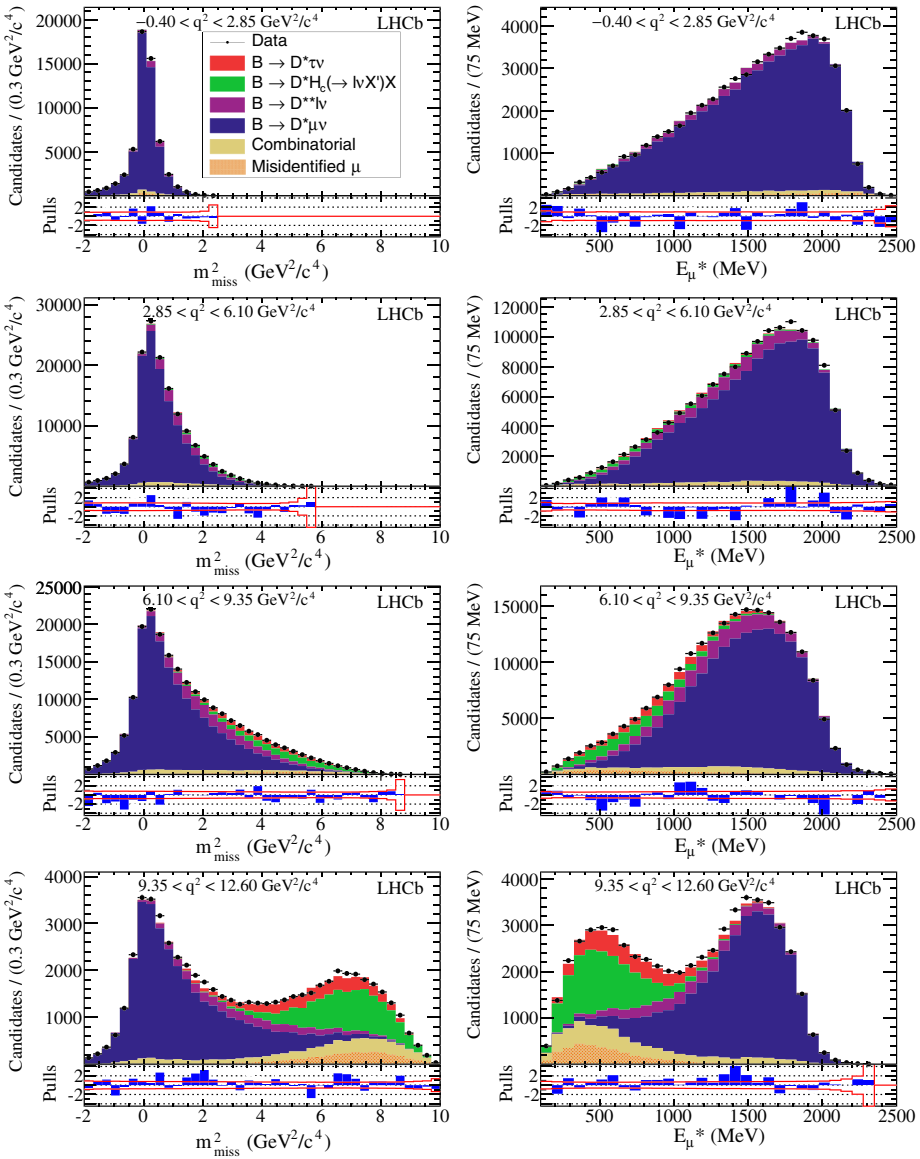
Semileptonic B decays

- FCCC are tree-level processes in the SM
- Measurement: ratio of BRs
- $R(X_c) = \frac{\mathcal{B}(B \to X_c \tau^+ \nu_\tau)}{\mathcal{B}(B \to X_c \mu^+ \nu_\mu)}$
- Sensitivity to possible new physics contributions coupling mainly to the 3rd generation
- τ reconstructed via muonic or hadronic channel
- $\tau^+ \to \mu^+ \nu_\tau \bar{\nu}_\mu$ (1 prong)
- $\tau^+ \to \pi^+ \pi^+ \pi^- \bar{\nu}_\tau$ (3 prongs)
- All LHCb measurements here utilise the full Run 1 dataset
- 3.0 fb^{-1} at 7 and 8 TeV





Muonic $R(D^*)$



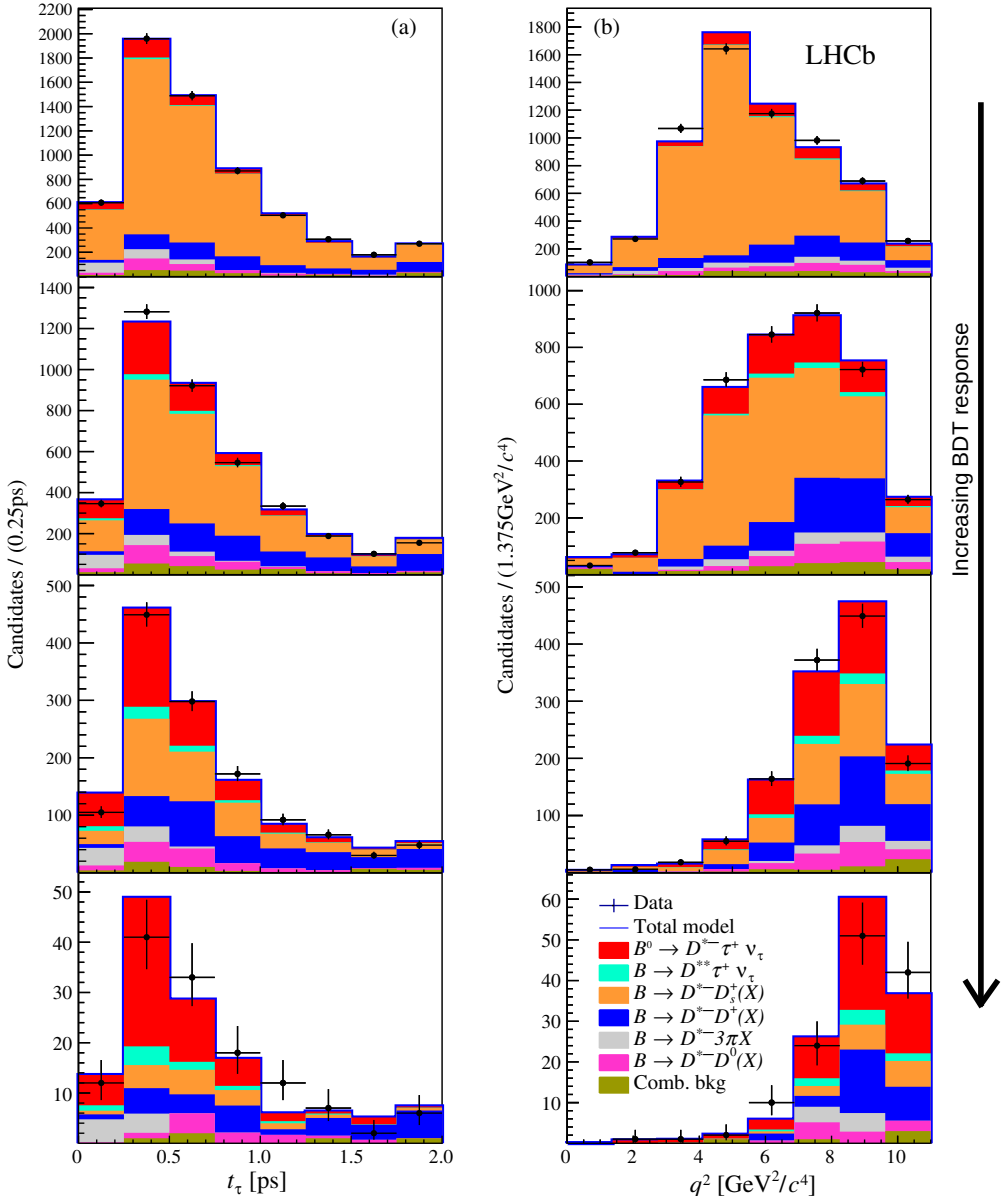
Increasing q2

- $R(D^*) = \frac{\mathcal{B}(B \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{*-}\mu^+\nu_\mu)}$
- $D^{*-} \to (\overline{D}^0 \to K^+\pi^-)\pi^-$
- $\tau^+ \to \mu^+\nu_\tau\bar{\nu}_\mu$
- 3D fit to m^2_{miss}, E^*_μ and q^2
- m^2_{miss}: squared missing mass
- E^*_μ: muon energy in centre-of-mass frame
- q^2: transferred 4-momentum to lepton pair
- Fit with templates from simulation
- $R(D^*) = 0.336 \pm 0.027 \pm 0.030$
- 1.9σ above SM prediction

[PRL 115 (2015) 111803]

Hadronic $R(D^*)$

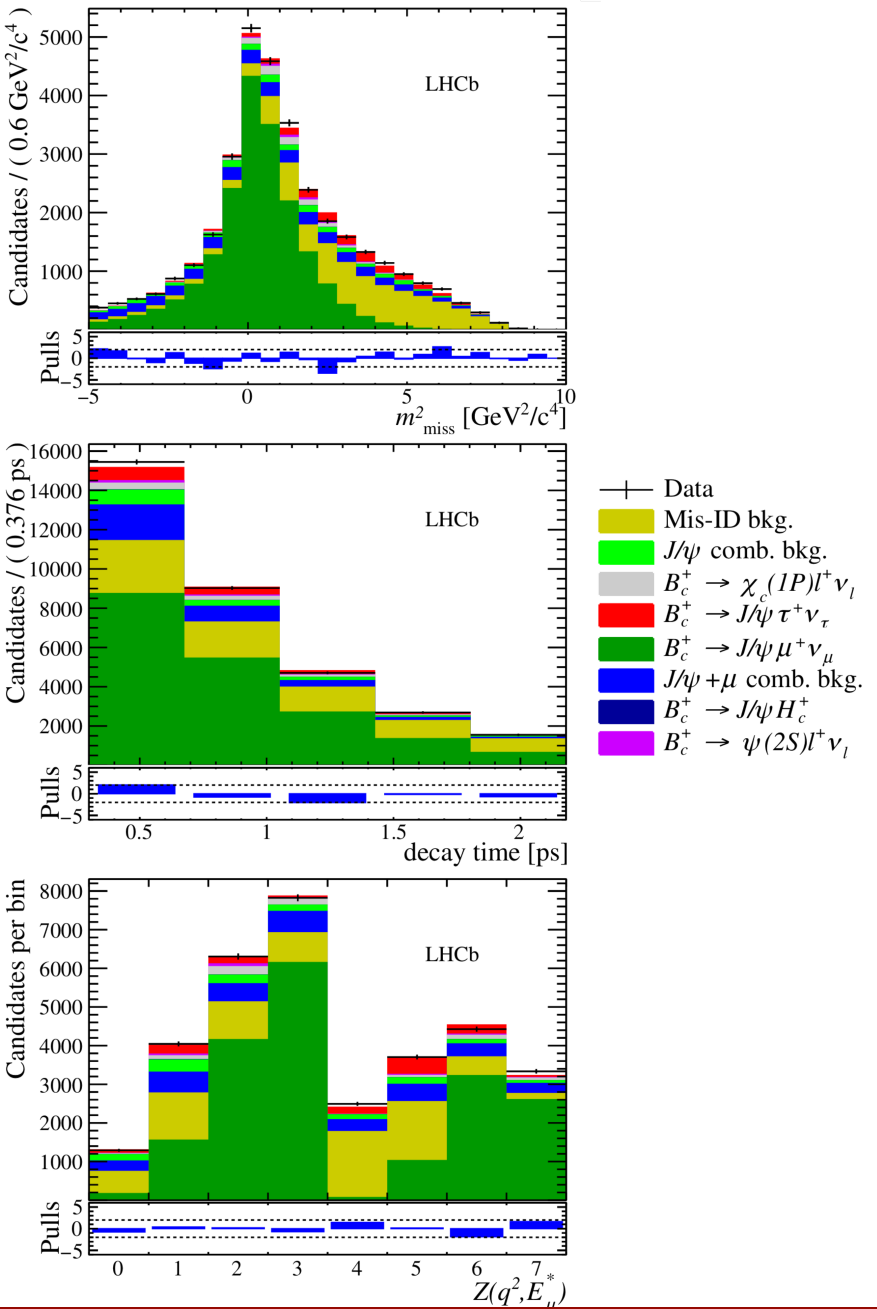
- $R(D^*) = \frac{\mathcal{B}(B \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B \to D^{*-}\mu^+\nu_\mu)}$
- $D^{*-} \to (\overline{D}^0 \to K^+\pi^-)\pi^-$
- $\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu}_\tau$
- The τ vertex can be measured
- No charged lepton in the final state, no background from semileptonic sources
- 3D fit to τ decay time, q^2 and BDT response with templates from simulation
- $R(D^*) = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$
- 0.9σ above SM prediction



[PRL 120 (2018) 171820], [PRD 97 (2018) 072013]

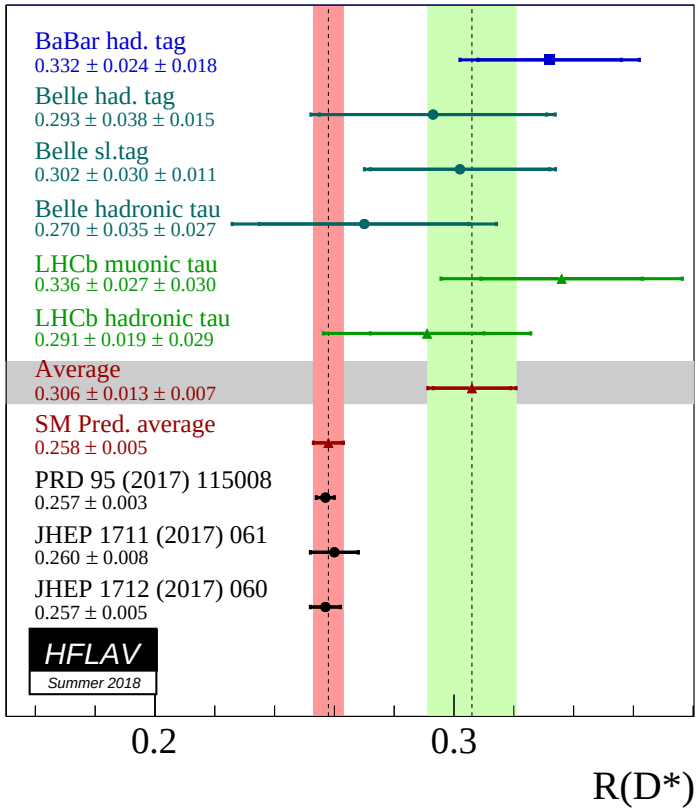
$R(J/\psi)$

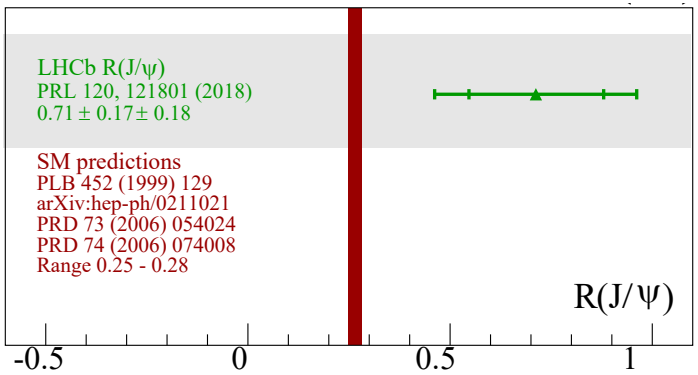
- $R(J/\psi) = \frac{\mathcal{B}(B \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B \to J/\psi \mu^+ \nu_\mu)}$
- $J/\psi \to \mu^+ \mu^-$
- $\tau^+ \to \mu^+ \nu_\tau \bar{\nu}_\mu$
- 3D fit to m^2_{miss}, decay time and $Z(E^*_\mu, q^2)$
- $Z(E^*_\mu, q^2)$: bin index in the (E^*_μ, q^2) plane
- Fit with templates from simulation
- First evidence of the decay $B_c^+ \to J/\psi \tau^+ \bar{\nu}_\tau$
- $R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$
- 2σ above SM prediction



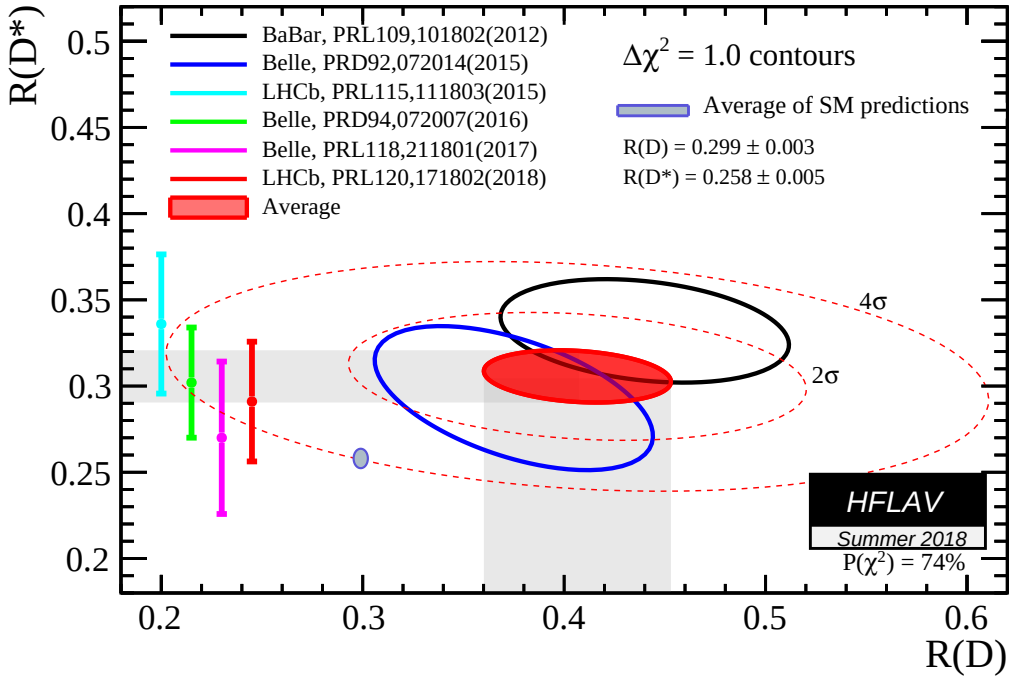
[PRL 120 (2018) 121801]

Summary of $R(D^*)$ and $R(J/\psi)$





[HFLAV]

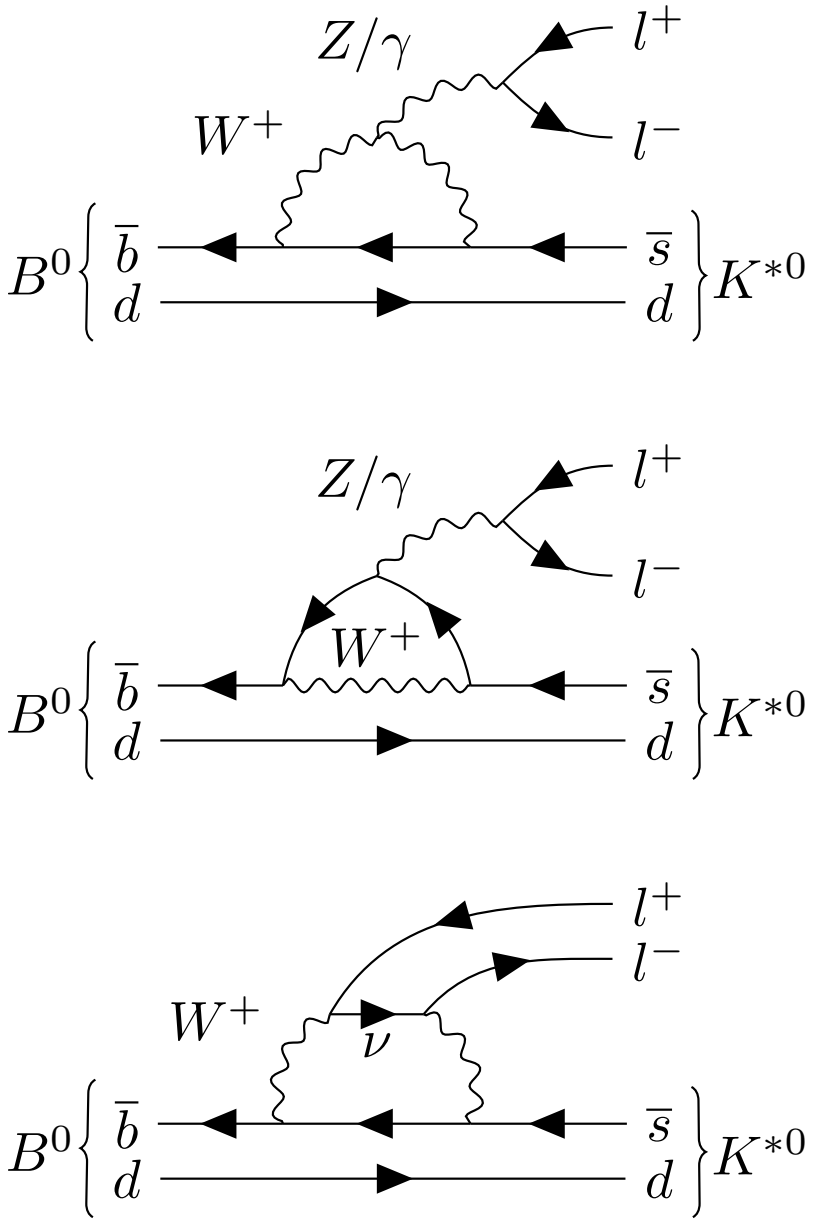


- All measurements of $R(D^*)$, $R(J/\psi)$ and $R(D)$ lie above the SM predictions
- $R(D^*)$ average is 3.0σ above the SM prediction
- Combination with $R(D)$ gives a tension of 3.8σ

LEPTON UNIVERSALITY TESTS WITH FLAVOUR-CHANGING NEUTRAL CURRENTS

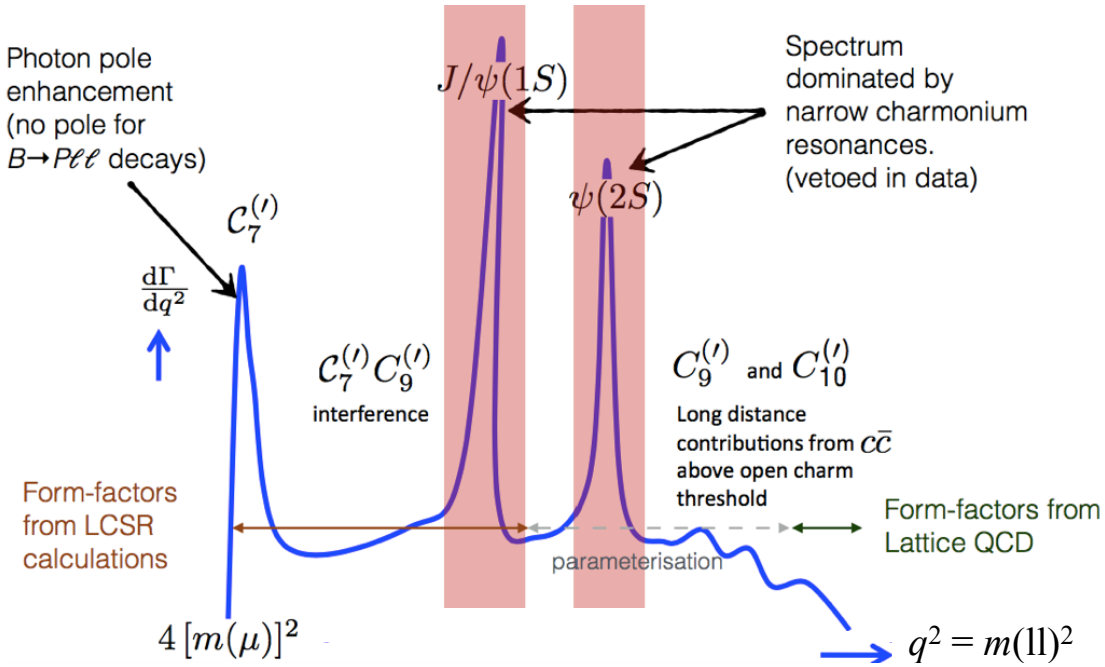
Phenomenology of $b \to sll$ transitions

- FCNC forbidden at tree level in the SM
- Rare decays, $\mathcal{B} \sim 10^{-6} - 10^{-7}$
- Highly sensitive to contribution from sources outside the SM
- Model-independent approach using effective, four-fermion point interactions
- $\mathcal{L}_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum_i C_i \mathcal{O}_i\right)$
- $\mathcal{O}_i$ are current-current operators
- C_i are complex coefficients (Wilson coefficients)
- Sensitivity in angular distributions and differential branching fractions



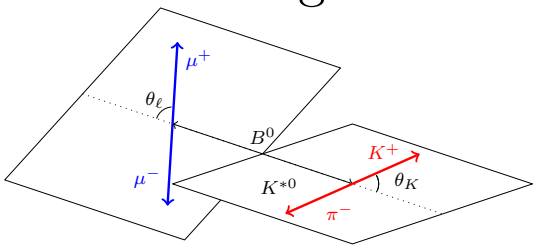
Operators and q^2 dependence

- Study of the differential branching fraction in bins of $q^2 = m(l^+l^-)$
- $\mathcal{O}_7$: electromagnetic penguin operator
- $\mathcal{O}_{9,10}$: semileptonic operators
- In order to remove long distance effects (i.e. $b \to (c\bar{c} \to ll)s$) the narrow charmonium resonances are vetoed

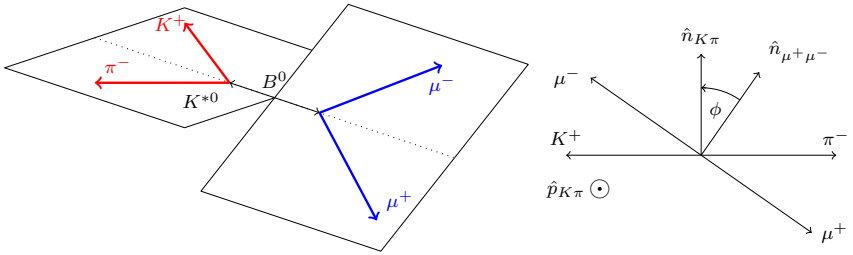


Angular observables

Study of the full angular distribution in bins of q^2



(a) θ_K and θ_ℓ definitions for the B^0 decay



(b) ϕ definition for the B^0 decay

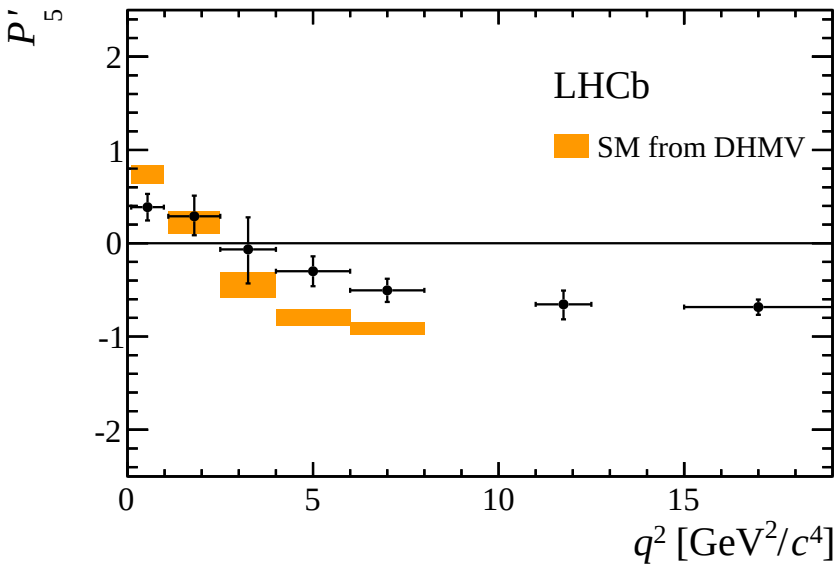
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^4(\Gamma+\bar{\Gamma})}{\mathrm{d}q^2\,\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_l$$
$$-F_\mathrm{L}\cos^2\theta_K\cos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

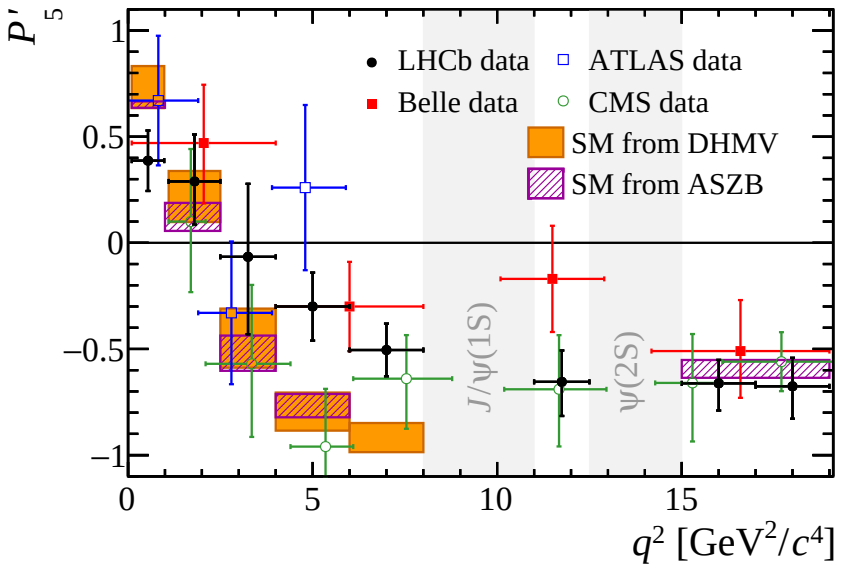
- A_{FB} is the forward-backward asymmetry of the dileptons
- S_j are CP-averaged combinations of the K^{*0} polarisation amplitudes
- F_L is the fraction of longitudinal polarisation of the K^{*0}
- They are all functions of C_7, C_9, C_{10}

Other cleaner variables, for which the hadronic form factor uncertainties cancel at leading order, can be defined

[JHEP 1305(2013)137)], [JHEP 02(2016)104]

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

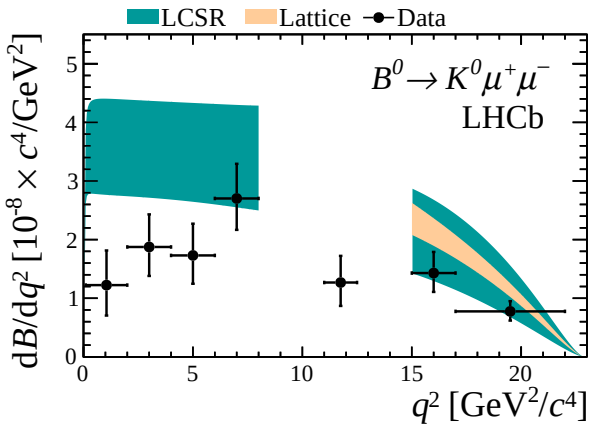


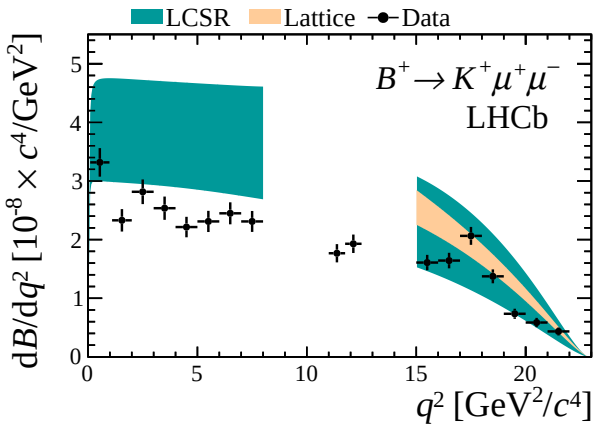


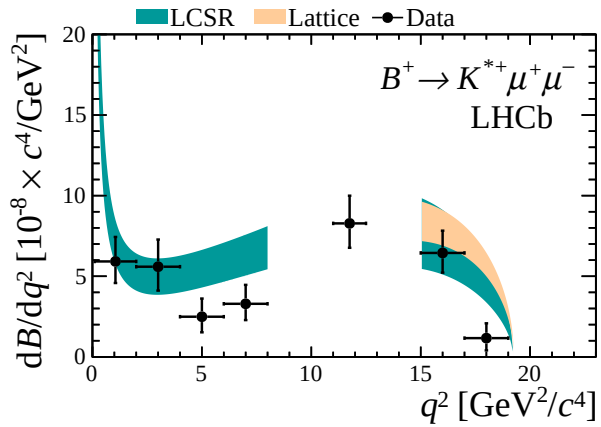
- Dataset: full Run 1
- $P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$ distribution shows local deviations with respect to SM
- Global significance of about 3.4σ (LHCb only)
- Measurements from other experiments are compatible

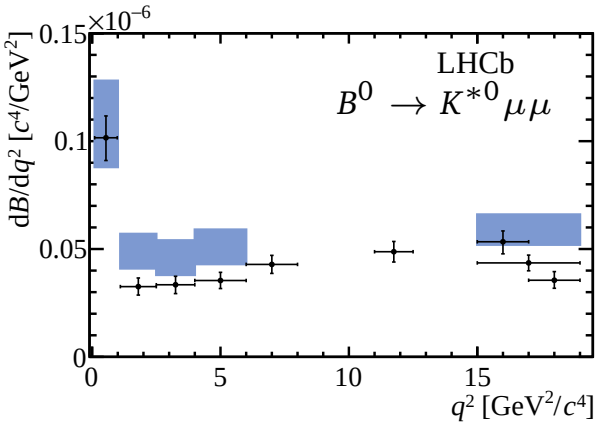
LHCb[JHEP 02(2016)104], ATLAS[arXiv:1805.04000], CMS[PLB 781(2018)517], Belle[PRL 118(2017)111801]

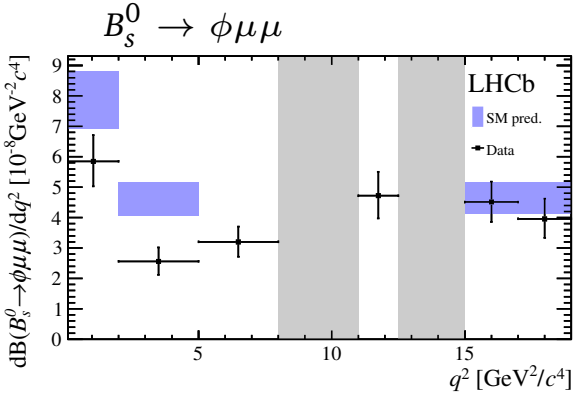
$b \to s\mu\mu$ differential branching fractions

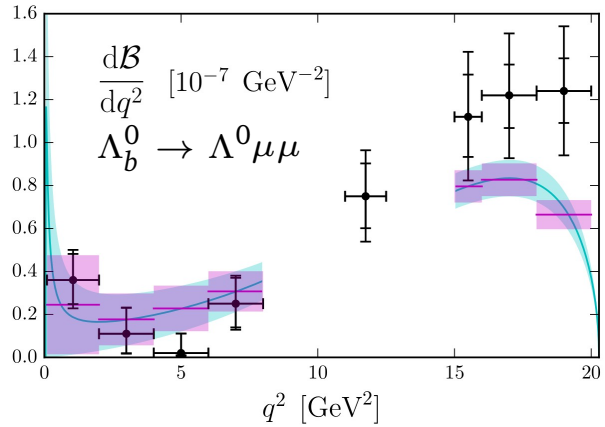








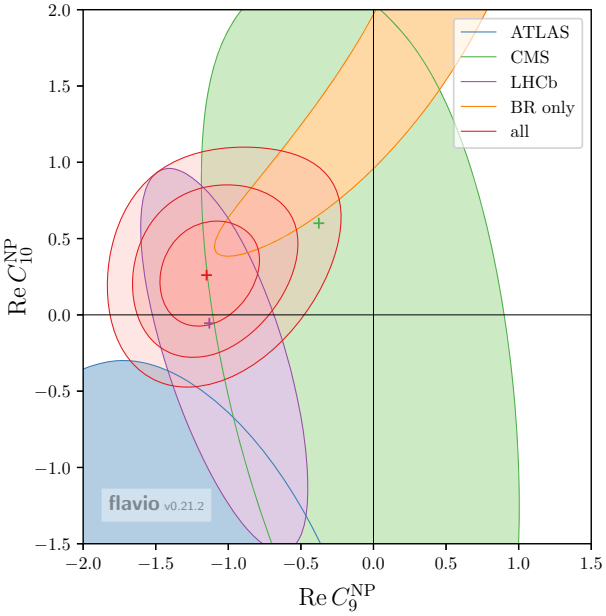


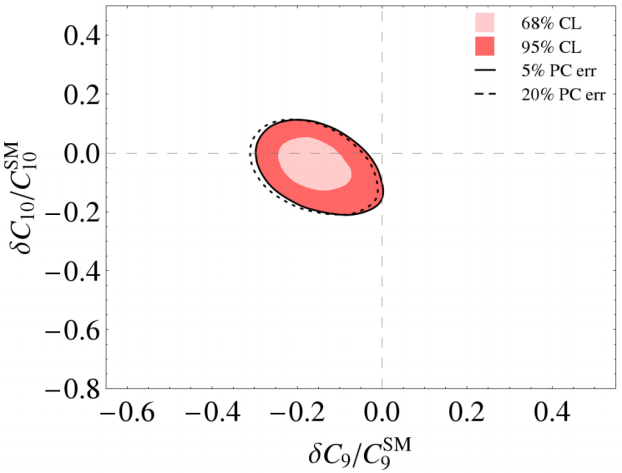


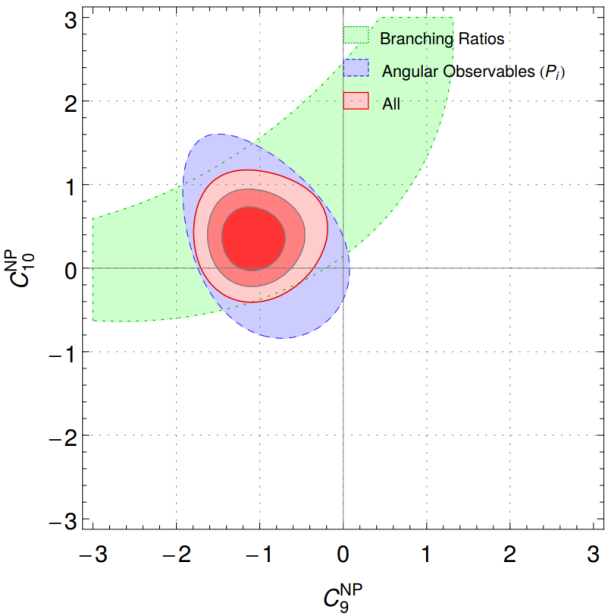
- Low-q^2 regions: results are consistently lower than the SM predictions
- Largest local discrepancy is 3.3σ for $B_s^0 \to \phi\mu\mu$

[JHEP 06(2014)133], [JHEP 04(2017)142], [JHEP 09(2015)179], [JHEP 06(2015)115], [PRD 93(2016)074501]

Global fit from $b \to s\mu\mu$ measurements







- Global fit to the real part of C_9 and C_{10}
- The best fit for several global analyses points towards a shift in C_9
- Discrepancy up to 5σ
- Discussion is ongoing about our understanding of QCD effects in branching fractions and angular observables

[JHEP 06(2016)092], [arXiv:1611.05060], [EPJC 77 6(2017)377]

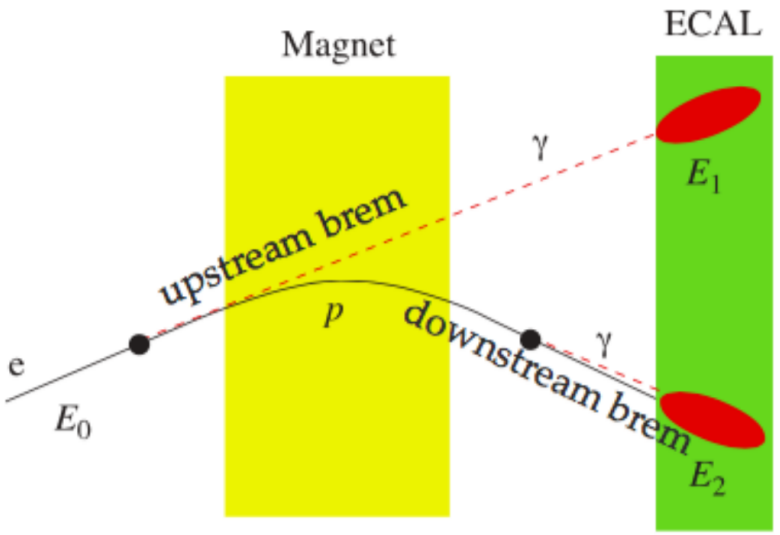
BF double ratios in $b \to sll$ decays: $R(K^{(*)})$

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

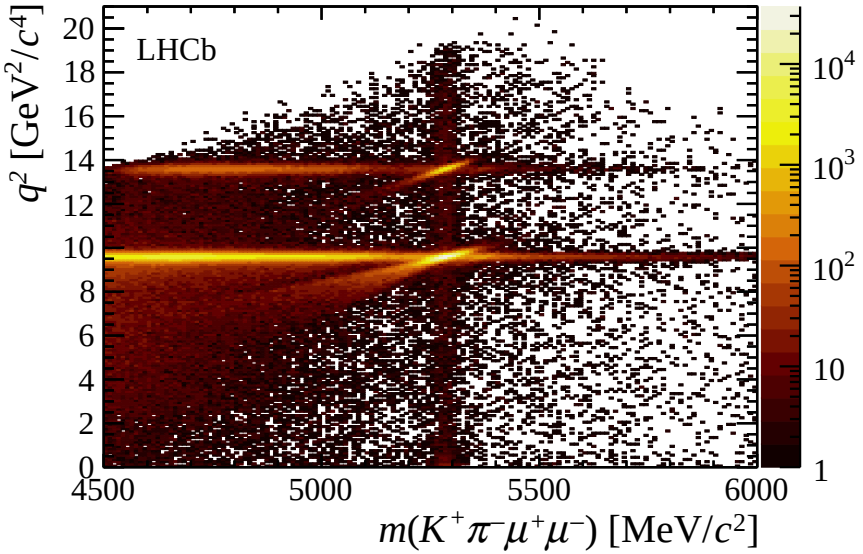
$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}(J/\psi \to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B \to K^{(*)}e^+e^-)}{\mathcal{B}(B \to K^{(*)}(J/\psi \to e^+e^-))}$$

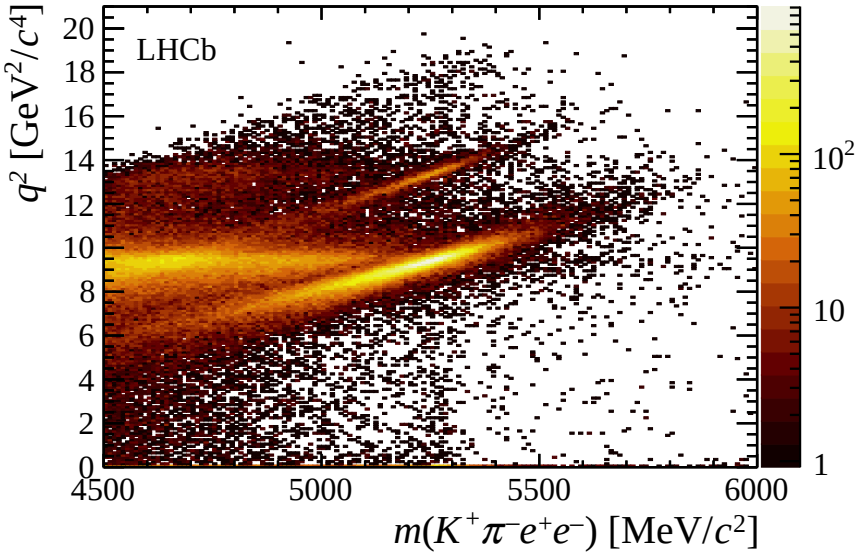
- Direct test of lepton universality in $b \to sll$ decays
- The double ratio reduces systematic uncertainties
- Selection between the muon and electron channel as similar as possible
- Challenging due to the differences between muons and electrons
  - Trigger
  - Efficiencies
  - Bremsstrahlung
  - Resolution

Muons and electrons in LHCb



- Electrons emit a large amount of bremsstrahlung that results in degraded momentum and mass resolutions
- Downstream brem: photon emitted after the magnet, momentum correctly measured
- Upstream brem: photon emitted before the magnet, momentum underestimated

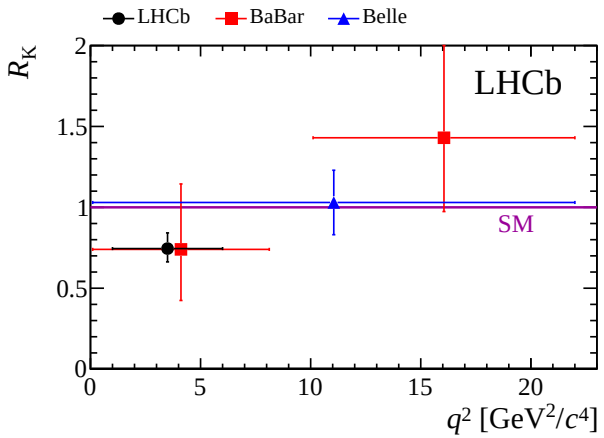




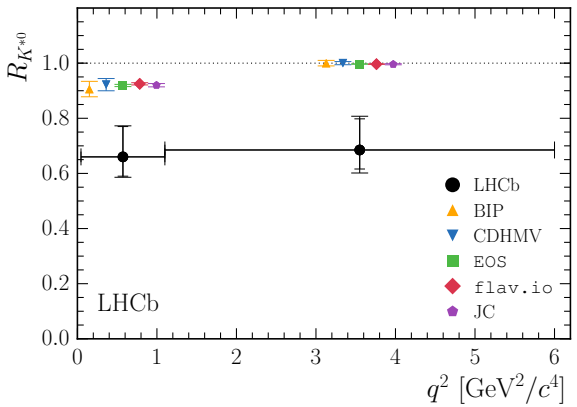
[JHEP 08(2017)055]

Results for $R(K)$ and $R(K^*)$

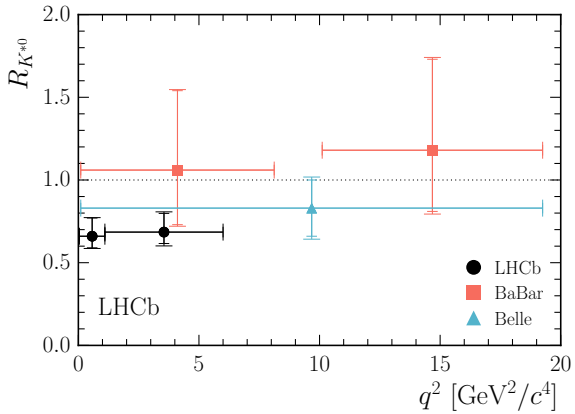
Datasets: full Run 1 (3 fb^{-1})



$R(K)$



$R(K^*)$



$R(K^*)$

- LHCb results are consistently lower than 1
- $R(K) = 0.745^{+0.090}_{-0.074} \pm 0.036$ (2.6σ) at central $q^2 \in [1.0, 6.0]$ GeV$^2/c^4$
- $R(K^*) = 0.66^{+0.11}_{-0.07} \pm 0.03$ $(2.1\sigma - 2.3\sigma)$ at low $q^2 \in [0.045, 1.1]$ GeV$^2/c^4$
- $R(K^*) = 0.69^{+0.11}_{-0.07} \pm 0.05$ $(2.4\sigma - 2.5\sigma)$ at central $q^2 \in [1.1, 6.0]$ GeV$^2/c^4$
- Results from B factories are compatible (with less precision)
- These results point to a shift in the muonic C_9 in accordance with the other anomalies detected in $b \to sll$ decays

[PRL 113(2014)151601], [JHEP 08(2017)055]

CONCLUSIONS AND PROSPECTS

Flavour-changing charged currents

- Three tests of lepton universality with semitauonic analyses
  - $R(D^*)$, muonic channel
  - $R(D^*)$, hadronic channel
  - $R(J/\psi)$, muonic channel
- All measurements fluctuate in the same direction
- 3.8σ deviation from SM when combining measurements of BaBar, Belle and LHCb on $R(D^*)$ and $R(D)$
- Many other analyses still ongoing
  - $b \to c l \nu$: $R(D^+)$, $R(D^0)$, $R(D_s^-)$, $R(\Lambda_c)$ ...
  - $b \to u l \nu$: $R(B \to pp\tau\nu)$, $R(\Lambda_b^0 \to p\tau\nu)$ ...
  - $c \to u l \nu$, with muons and electrons (challenging in LHCb)
- Interest also in angular observables
- Inclusion of Run 2 data will bring 5 times more statistics

Flavour-changing neutral currents

- A large set of anomalies has been observed in $b \to sll$ decays
- They all point to the same direction, i.e. additional contribution with respect to the SM in order to accommodate the data
- Deviations range between $2.1 - 2.6\sigma$
- Many more analyses are ongoing in this sector
- Inclusion of Run 2 data might already turn hints into evidences

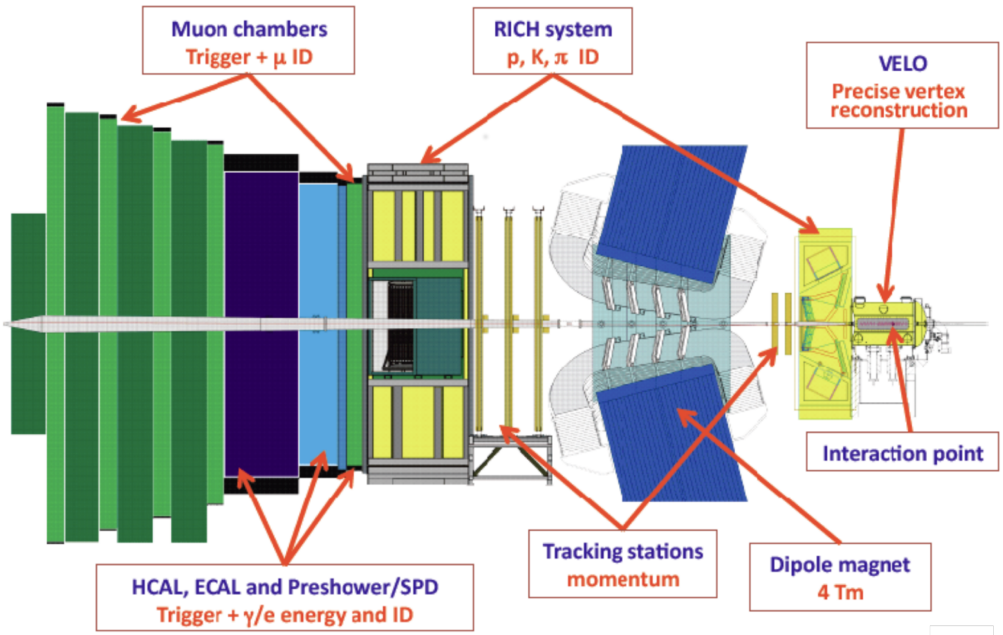
Observable	q^2 interval	Measurement	Extrapolations		
		$3\,\text{fb}^{-1}$	$8\,\text{fb}^{-1}$	$22\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$
$R(K)$	$1.0 < q^2 < 6.0\,\text{GeV}^2$	$0.745^{+0.090}_{-0.074} \pm 0.036$	0.046	0.025	0.016
$R(K)$	$15.0 < q^2 < 22.0\,\text{GeV}^2$	-	0.043	0.023	0.015
$R(K^*)$	$0.045 < q^2 < 1.1\,\text{GeV}^2$	$0.66^{+0.11}_{-0.07} \pm 0.03$	0.048	0.026	0.017
$R(K^*)$	$1.1 < q^2 < 6.0\,\text{GeV}^2$	$0.69^{+0.11}_{-0.07} \pm 0.05$	0.053	0.028	0.019
$R(K^*)$	$15.0 < q^2 < 19.0\,\text{GeV}^2$	-	0.061	0.033	0.021

[arXiv:1709.10308]

BACKUP

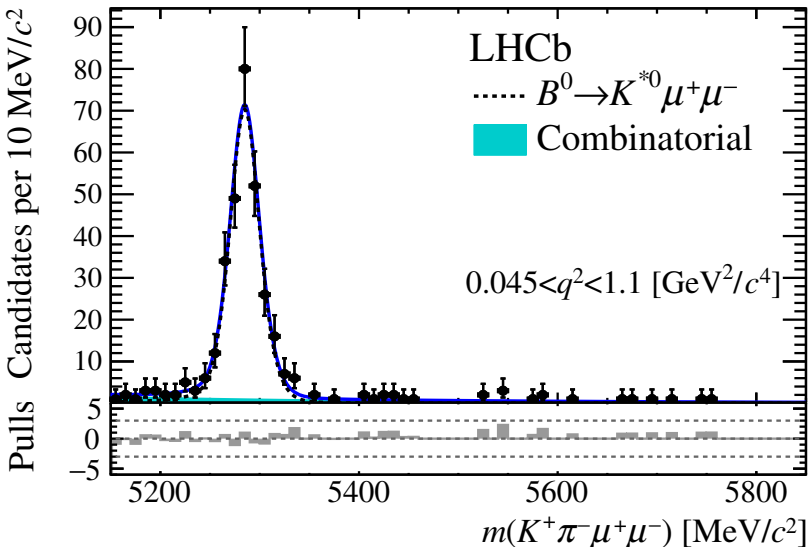
The LHCb experiment at CERN

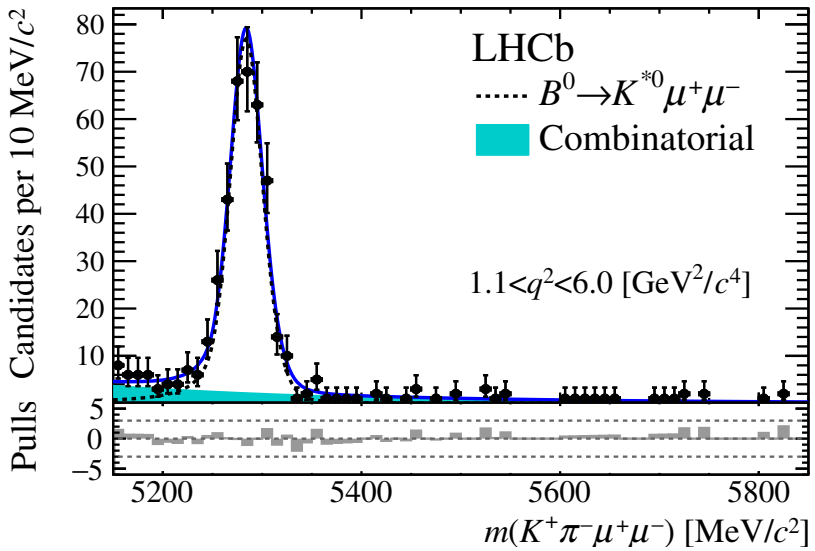
- Single arm spectrometer designed for high precision flavour physics measurements
- Pseudorapidity range $\eta \in [2, 5]$
- Highly efficient particle identification
- Very good momentum and IP resolution
- Excellent primary and secondary vertex reconstruction

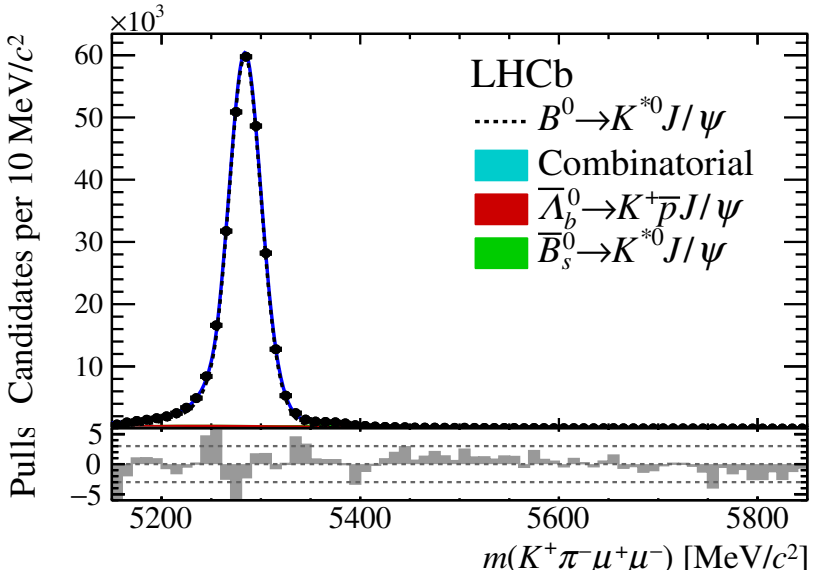


[JINST 3 (2008) S08005], [IJMPA 30 (2015) 1530022]

Fit to $m(K\pi\mu\mu)$

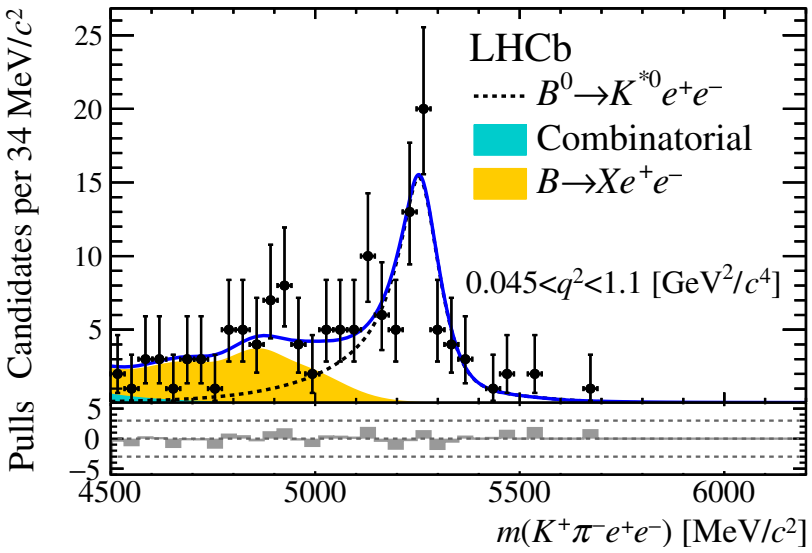


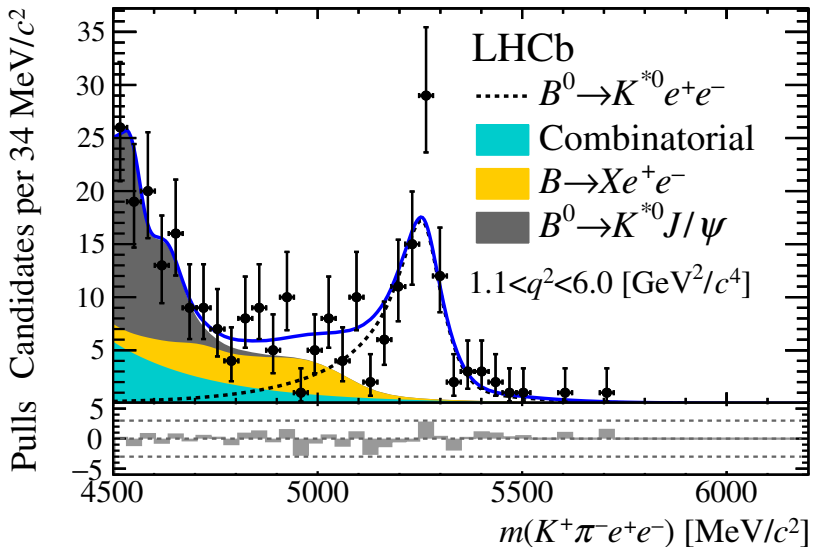


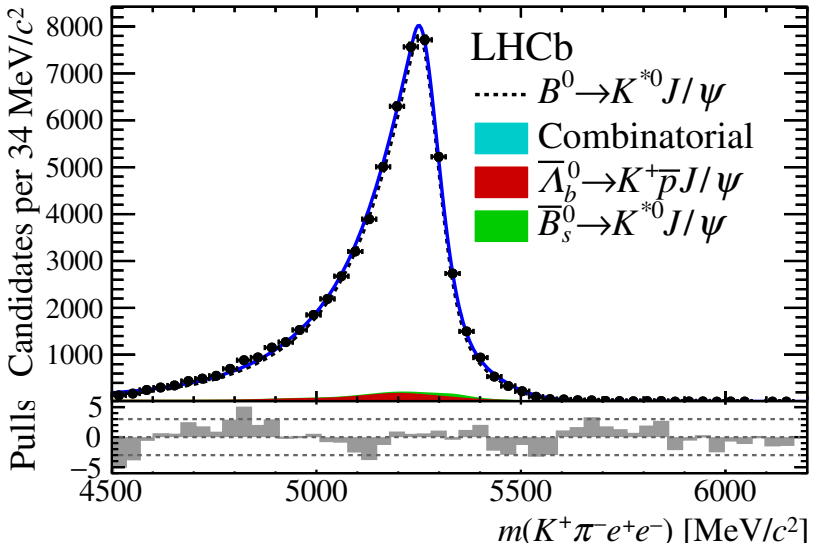


[JHEP 08(2017)055]

Fit to $m(K\pi ee)$







[JHEP 08(2017)055]