Lepton Flavour Universality tests with B decays at LHCb

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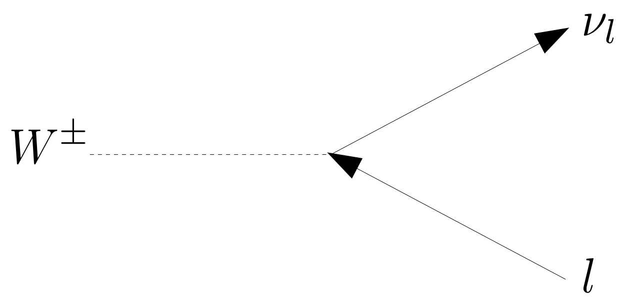
Lepton Flavour Universality

- In the Standard Model the electroweak coupling of the gauge bosons to leptons is independent of the lepton flavour:
  - the branching fractions of decays involving leptons do not depend on the lepton kind: the only differences between e, μ and τ are the phase space and helicity-suppressed contributions.



→ Any violation of lepton universality would be a clear sign of physics beyond the Standard Model

- Over the years LFU has been tested in several systems providing very strong limit:
  - More significant tests involve the 1° and 2° quarks and leptons families.

- A large class of SM extensions contain new interactions that involve third generation of quarks and leptons
  - Higgs-like charged scalar: $H^{\pm}$, new vectors coupled to SM Higgs doublet, leptoquarks, 2 Higgs doublets model (2HDM type II or III)…

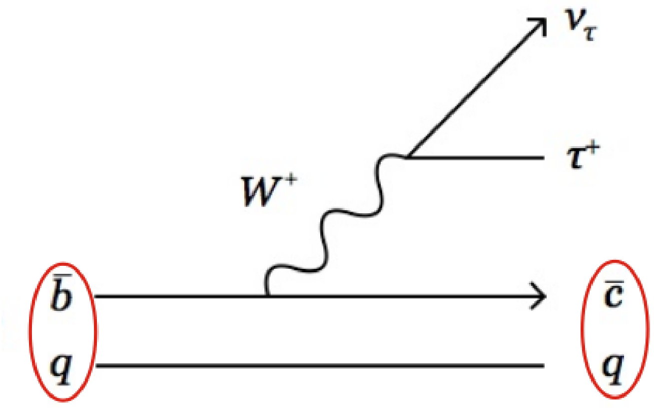
Semileptonic Decays

- The contributes to decay rate can be factorized in weak and strong part
  - The theoretical calculation are simplified.

$$\frac{d\Gamma(B\to Xl\nu)}{dq^2} \propto G_F^2 |V_{bq}|^2 f(q^2)^2$$

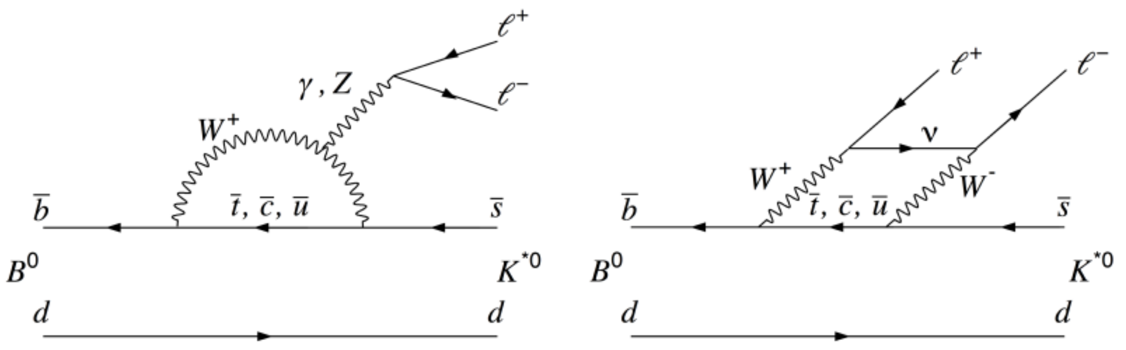
  - The lepton universality ratios further cancel the theoretical uncertainties

Charged current decays: b → c l ν



- Tree level, large BR

Neutral current decays: b → s l l

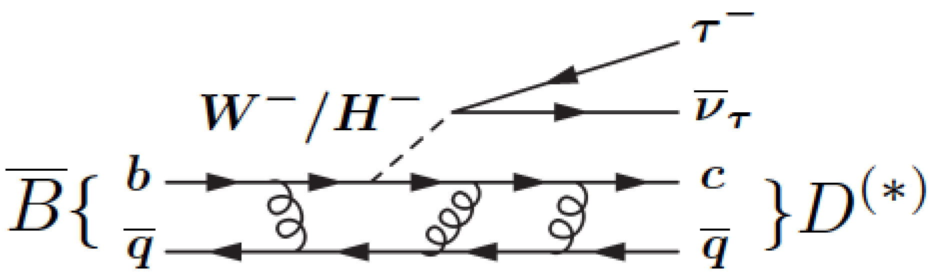


- FCNC, Loop diagram, low BR

b→clν: R(D*)

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

- Tree level decays → large branching fractions.
- Cancel QCD uncertainties.
- Precise prediction: R(D*) = 0.252 ± 0.003 (PRD85 (2012) 094025).
- R(D*) sensitive to any physics model favoring 3rd generation leptons for example leptoquarks or charged Higgs.



- LHCb measurement:
  - R(D*) where $\tau \to \mu\nu_\mu\nu_\tau$ (PRL115,111803(2015))
  - R(D*) where $\tau \to \pi\pi\pi(\pi^0)\nu_\tau$ (Phys. Rev. Lett. 120, 171802 (2018))

R(D*) with hadronic τ decays

PRL115,111803(2015)

- Final states: $D^{*-} \to \overline{D}^0 (\to K^+ \pi^-) \pi^-$ $\tau \to \pi\pi\pi(\pi^0)\nu_\tau$
  - \+ good tau vertex reconstruction
  - \- large hadronic backgrounds:
    - $B \to D^* 3\pi X$ (BF ~ 100x signal)
    - $B \to D^* D_s X$ (BF ~10x signal)

- R(D*) is obtained by

$$R(D^*) = K(D^*) \times \frac{Br(B^0 \to D^{*-} 3\pi)}{Br(B^0 \to D^{*-} \mu^+ \nu_\mu)}$$

[~4% precision, PDG2017]

[~2% precision, HFLAV 2016]

- the measured ratio is K(D*):

$$K(D^*) \equiv \frac{Br(B^0 \to D^{*-} \tau^+ \nu_\tau)}{Br(B^0 \to D^{*-} 3\pi)} = \frac{N_{D^*\tau\nu_\tau}}{N_{D^*3\pi}} \times \frac{\varepsilon_{D^*3\pi}}{\varepsilon_{D^*\tau\nu_\tau}} \times \frac{1}{Br(\tau^+ \to 3\pi(\pi^0)\bar{\nu}_\tau)}$$

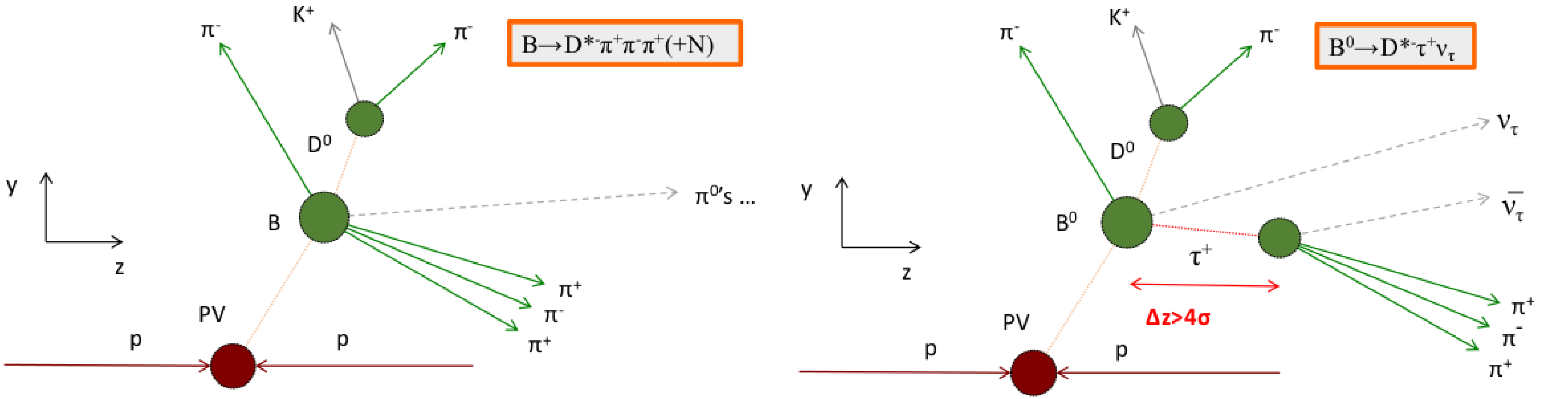
- $N_{D^*3\pi}$ from a unbinned likelihood fit to m(D* πππ).
- $N_{D^*\tau\nu}$ number of signal events.

- Signal and normalization have the same visible final states → most of the systematic uncertainties cancel in the ratio (PID, trigger and selection).

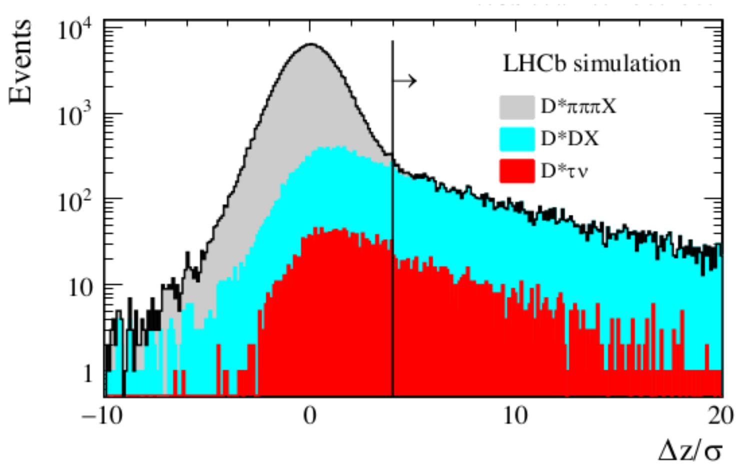
$H_b \to D^*3\pi X$

- The main background is due to $H_b \to D^*3\pi X$ (BF ~ 100x signal)

PRL115,111803(2015)



- Suppressed by requiring the τ vertex to be downstream wrt B vertex along beam direction with a 4σ significance

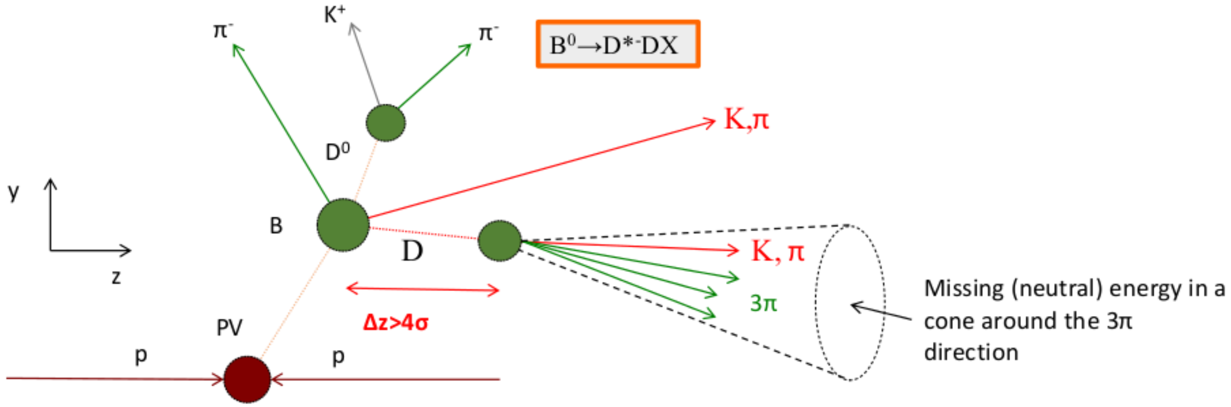


- Reduction of 3 orders of magnitude
- Signal efficiency = 35 %

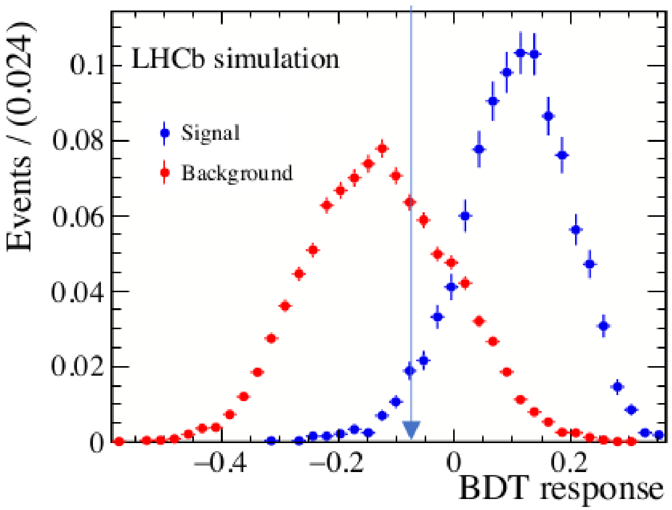
Double charmed background

PRL115,111803(2015)

- Remaining B meson double charmed decays are of type $B \to D^* D(3\pi Y)X$.
- Veto on candidates with extra charged particles compatible with B and 3π vertices
- BDT is based on
  - Variables aimed to isolate other charge tracks;
  - Neutral isolation BDT;
  - Different resonant structure of $D^*3\pi$ system;



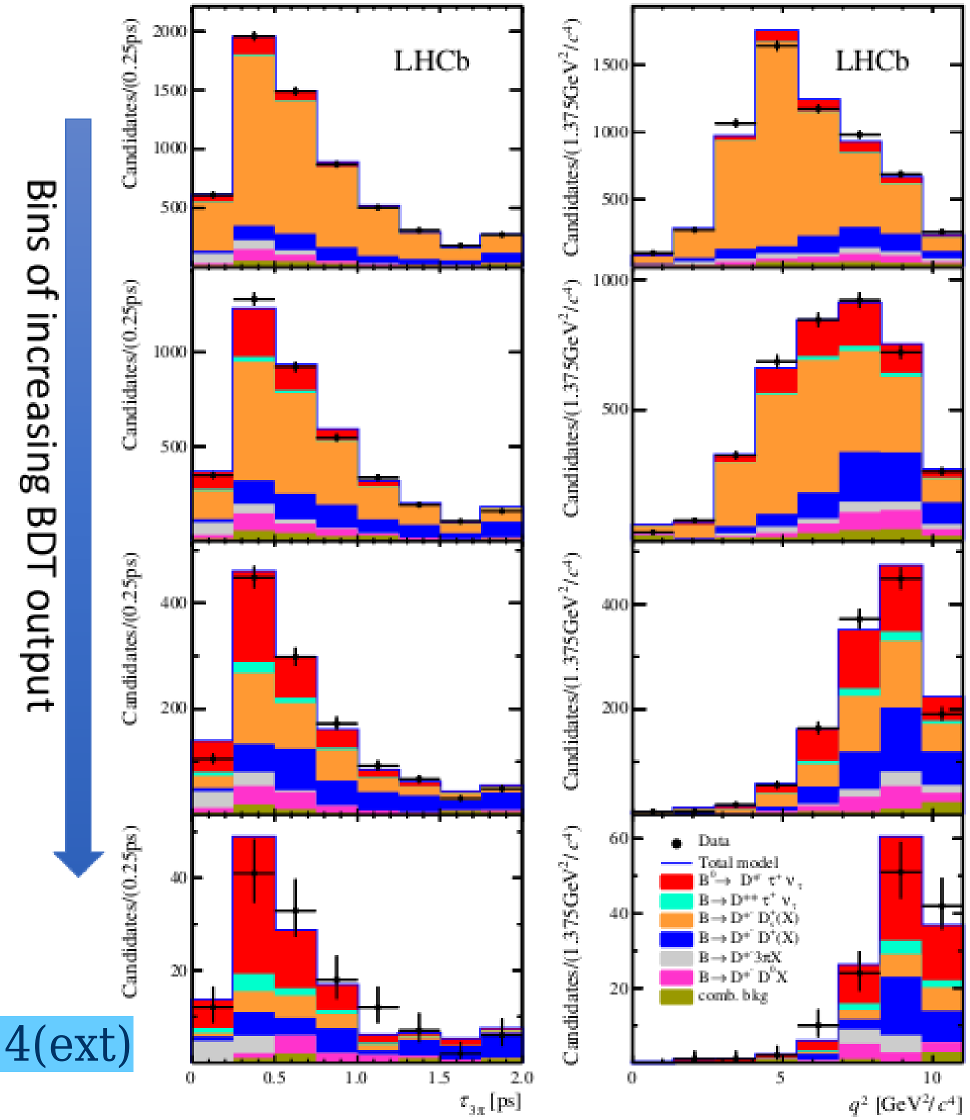
- High BDT region is used to extract the signal: BDT > −0.075.



Fit procedure

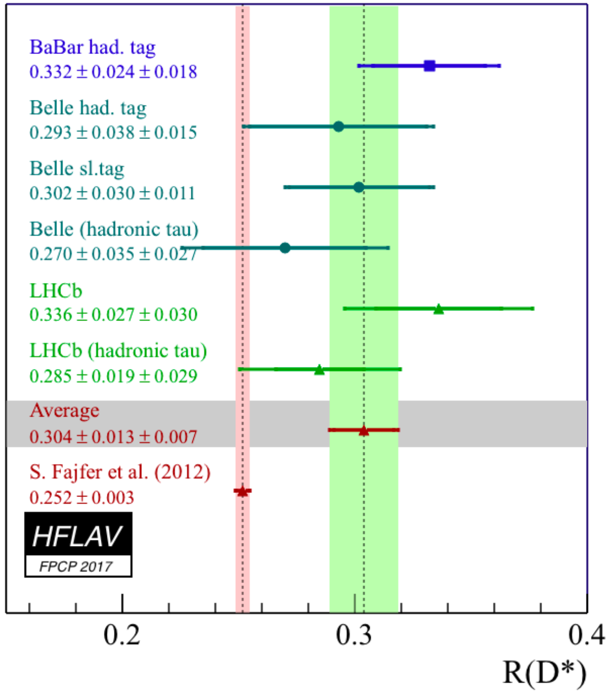
PRL115,111803(2015)

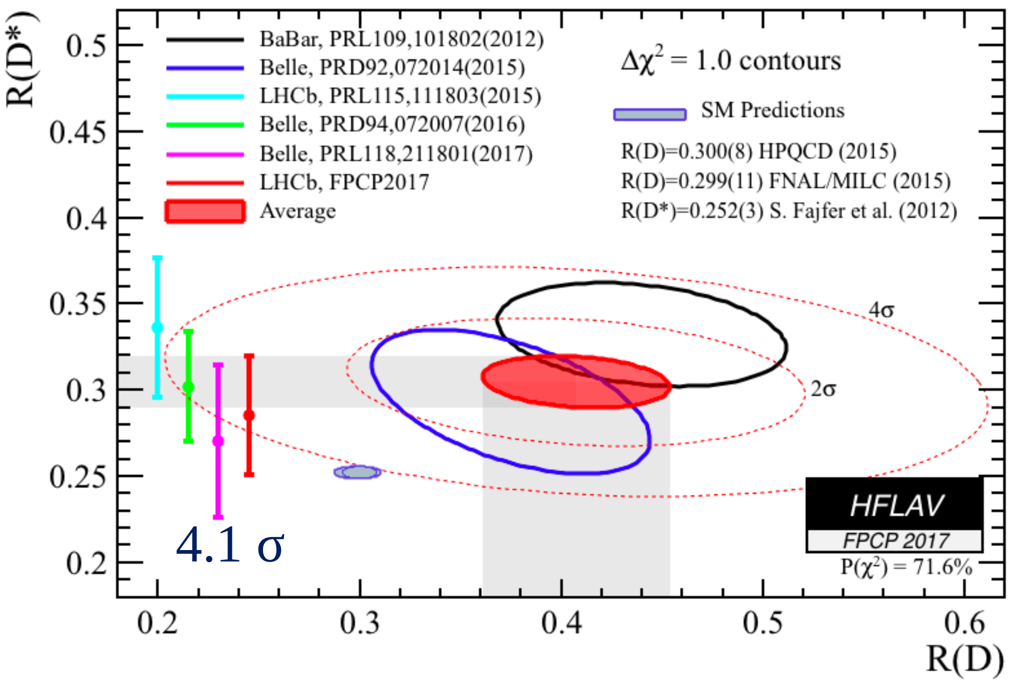
- A 3D extended maximum likelihood template fit is performed on data to extract signal yield:
  - BDT output
  - τ decay time
  - q^2
- run1 data, 3 fb^{-1} of data.
- $N_{D^*\tau\nu} = 1300 \pm 85$
- K(D*) = 1.93 ± 0.13(stat) ± 0.13(sys)
- R(D*) = 0.285 ± 0.019(stat) ± 0.025(sys) ± 0.014(ext)



R(D*) measurements combination

- $R(D^*)_{\text{HADRONIC LHCb}}$ = 0.285 ± 0.019 (stat) ± 0.025 (syst) ± 0.014 (ext)
- $R(D^*)_{\text{MUONIC LHCb}}$ = 0.336 ± 0.027(stat) ±0.030(syst)
- LHCb average: R(D*) = 0.306 ± 0.027 → 2.1σ above the SM prediction
- HFLAV world average: R(D*) = 0.304 ± 0.015 → 3.4 σ above the SM
- HFLAV average of R(D) and R(D*) is 4.1 σ from the SM prediction





$b \to c l \nu$: R(J/ψ)

Phys. Rev. Lett.120, 121801 (2018)

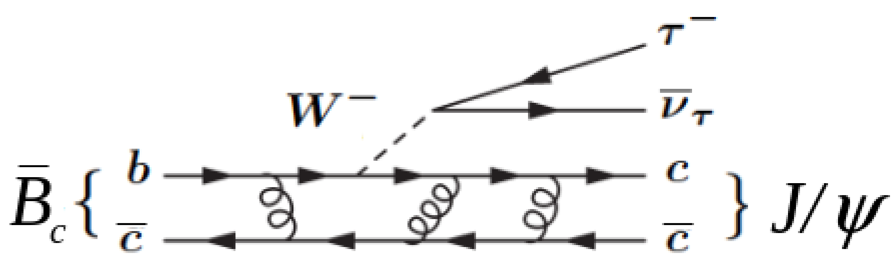
$$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}$$

- Additional handle for investigating:
  - The source of theoretical and experimental uncertainties;
  - The origin of the lepton universality coupling.

- Similar to R(D*) measurement.

- Small hadronisation factor: B_c meson are produced 200 times less than B^0.

- B_c decay form factors not yet unconstrained experimentally
  → prediction of R(J/ψ) affected by form factor uncertainties: R(J/ψ) ∈ [0.25,0.28]
  [PLB452 (1999) 120, arXiv:0211021, PRD73 (2006) 054024, PRD74 (2006) 074008]



$b \to c l \nu$: $R(J/\psi)$

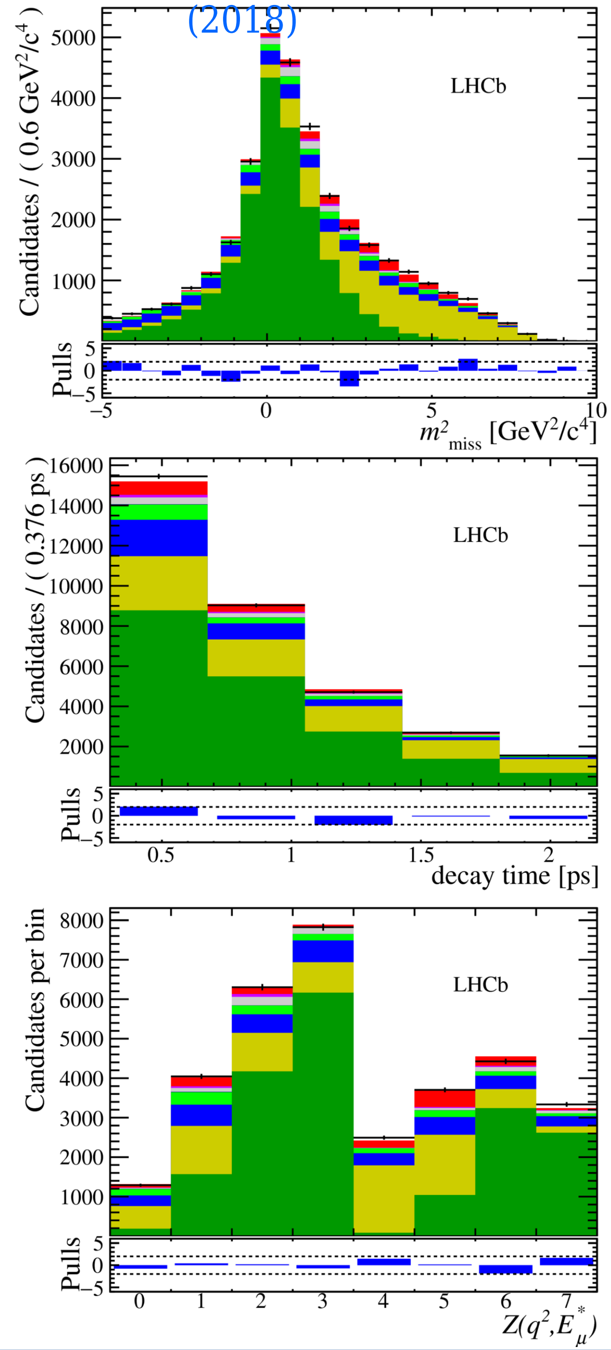
Phys. Rev. Lett.120, 121801 (2018)

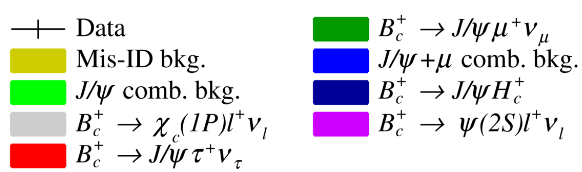
- Final states: $J/\psi \to \mu^+ \mu^-$ $\tau \to \mu \nu_\mu \nu_t$
- Identical reconstructed final state for semimuonic and semitauonic channel.
- In the B_c rest frame, four kinematics variables allow to distinguish $B_c \to J/\psi \tau \nu$ and $B_c \to J/\psi \mu \nu$:
  - $m^2_{miss} = (p_{Bc} - p_{J/\psi\mu})^2$
  - $q^2 = (p_{Bc} - p_{J/\psi})^2$
  - E^*_μ: energy of unpaired muon in the B_c centre of mass frame
  - τ_{Bc}

$b \to c l \nu$: $R(J/\psi)$

- Main background:
  - $B \to J/\psi h$, h misID as μ.
- Maximum Likelihood Fit to binned m^2_{miss}, τ_{Bc} and $Z(q^2, E^*_\mu)$ distributions with 3D templates.
- Z is a categorical variable separating the candidates in bins of q^2 e E^*_μ
- run1 data, 3 fb^{-1} of data.
- $R(J/\psi)$ = 0.71 ± 0.17(stat) ± 0.18(sys)
  → 2σ above the SM prediction
- First evidence for the decay $B_c \to J/\psi \tau \nu$.
- Main systemtics due to the form factors and the size of the simulation sample.

Phys. Rev. Lett.120, 121801 (2018)





$b \to sll$ as probe of NP

- Flavour Changing Neutral Current transitions → proceed only via loop diagrams
- Suppressed in SM → more sensitive to NP
- NP could couple in a non universal way to the different lepton families.

- Comparing the rates of $B \to H\ \mu^- \mu^+$ and $B \to H\ e^- e^+$ allows precise test of lepton flavour universality

$$R_{\mathrm{H}}\left[q^2_{\min}, q^2_{\max}\right] = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B\to H\mu^+\mu^-)}{\mathrm{d}q^2}}{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B\to He^+e^-)}{\mathrm{d}q^2}}\ , \quad q^2 = m^2(\ell\ell)$$

$$H = K, K^*, \phi, \ldots$$

- The hadronic uncertainties in the theoretical predictions cancel.
- SM expectation: $R_H = 1$, neglecting lepton masses.

- LHCb measurements:
  - R_K : Phys. Rev. Lett. 113, 151601 (2014)
  - R_{K^*} : JHEP 08 (2017) 055

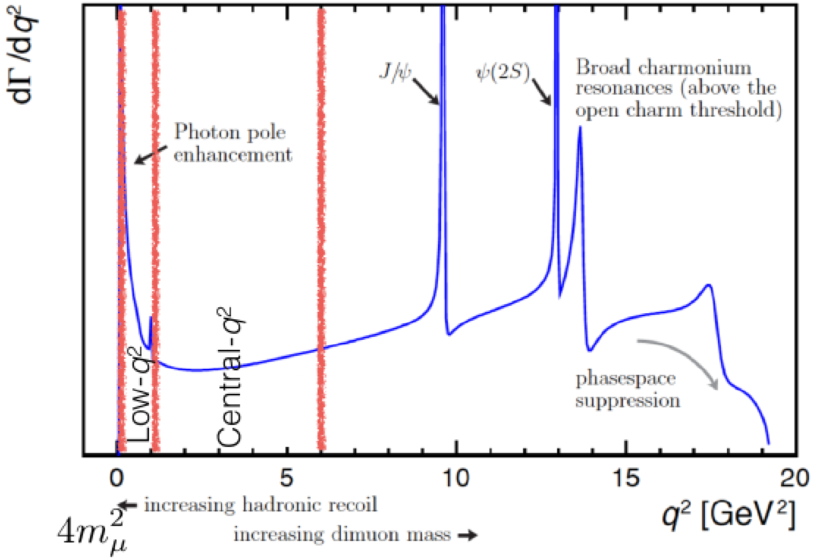
R(K*)

$$R_{K^{*0}}\left[q^2_{\text{min}}, q^2_{\text{max}}\right] = \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B^0\to K^{*0}\mu^+\mu^-)}{\mathrm{d}q^2}}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} \mathrm{d}q^2 \frac{\mathrm{d}\Gamma(B^0\to K^{*0}e^+e^-)}{\mathrm{d}q^2}}, \quad K^*(892)^0 \to K^+\pi^-$$

- The double ratio of rare to J/psi channel is used to reduce the systematic uncertainties:

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0\to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0\to K^{*0}J/\psi(\to\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0\to K^{*0}e^+e^-)}{\mathcal{B}(B^0\to K^{*0}J/\psi(\to e^+e^-))}$$

- The measurement is performed in two bins:
  - Low q^2 bin: [0.0045, 1.1] GeV^2
  - central q^2 bin: [1.1, 6] GeV^2



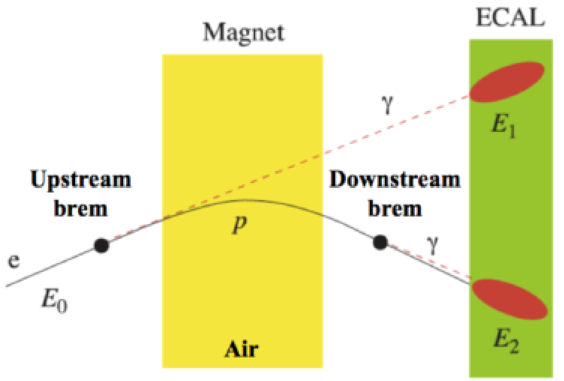
- Extremely challenging due to significant differences in the way μ and e interact with the detector:
  - bremsstrahlung
  - trigger

JHEP 08 (2017) 055

Bremsstrahlung and Trigger

JHEP 08 (2017) 055

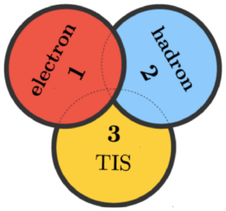
- Electron reconstruction is more difficult than muon due to bremsstrahlung.
- The electrons emit a large amount of bremsstrahlung that results in a degraded B momentum and mass resolution.
- Recovery momentum procedure: extrapolation of the electron track upstream and addition of the bremsstrahlung calorimeter cluster to electron momentum.



- Due to higher occupancy of the calorimeters compared to the muon stations, hardware trigger thresholds on the electron E_T are higher than on the muon p_T

  (L0 Muon, p_T >1.5,1.8 GeV)

  → partial loss of electron signal
  → to partially mitigate this effect 3 exclusive trigger categories are considered:

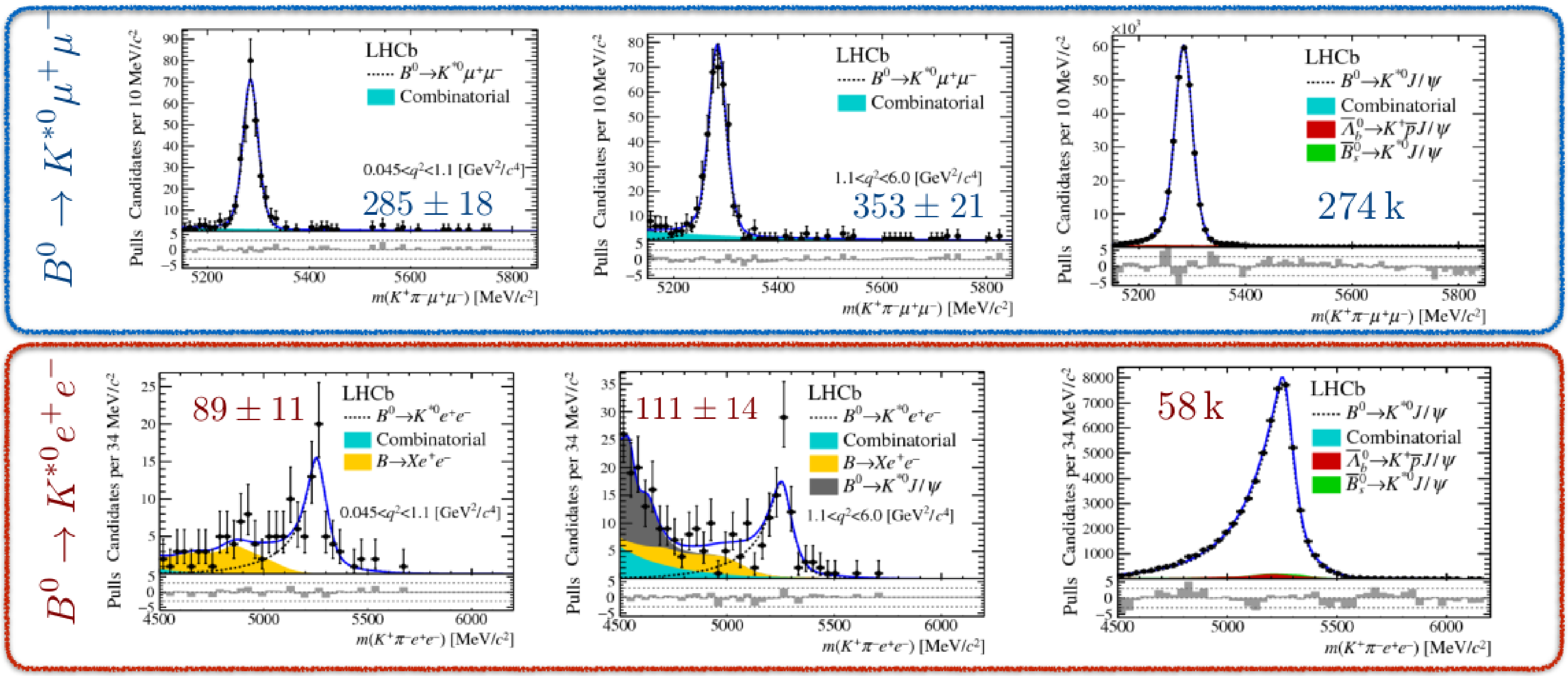


Fit Procedure

JHEP 08 (2017) 055

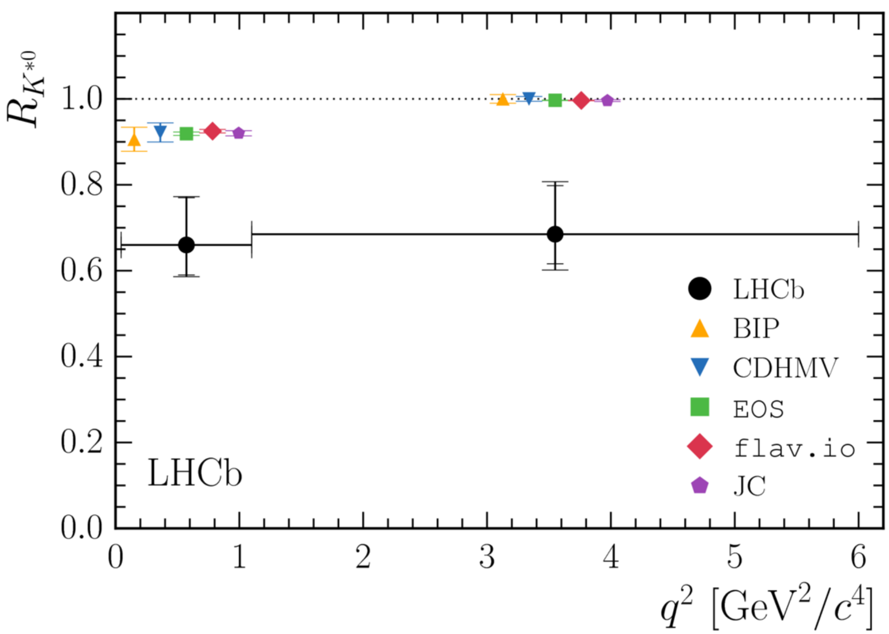
- Fit to B mass in lower and central dilepton transferred momentum region.
- Simultaneous fit to resonant and not resonant data, particularly for the electron decays splitted in 3 trigger categories.

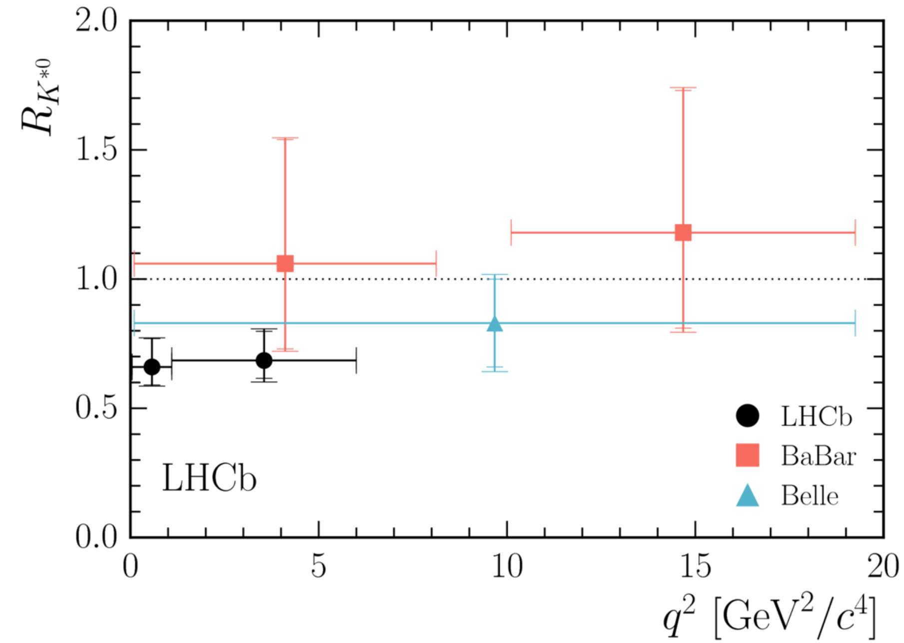
low q^2 bin | central q^2 bin | normalization channel



R(K*) result

- Precision of the measurement driven by statistics of electron samples.
- Compatibility with the SM:
  - low q^2 bin: 2.1-2.3 standard deviation;
  - central q^2 bin: 2.4-2.5 standard deviation.





- BaBar: PRD 86 (2012) 032012
- Belle: PRL 103 (2009) 171801
- LHCb: JHEP 08 (2017) 055

Conclusion

- Lepton Flavour Universality test are a clean probe to NP, completing the direct researches.
- Both in tree and loop level semileptonic B decays present anomalies with respect to the SM.
- All measurements presented are performed using run 1 data and are dominated by statistical error → run 2 LHC data.
- The hadronic LHCb R(D*) measurement is one of the best single measurements having the smallest statistical error. HFLAV average of R(D) and R(D*) is 4.1 σ from the SM prediction.
- Recent 2σ discrepancy in the same direction observed by LHCb in $B_c \to J/\psi \tau \nu$.
- The compatibility of R(K*) result with respect to the SM predictions is of 2.2-2.5 standard deviations in each q^2 bins. It is particularly interesting given a similar behavior in R(K).
- Other ongoing R measurement at LHCb:
  - Tree: R(D), $R(\Lambda_c^{(*)})$,…
  - Loop: $R(K_S)$, R(Φ),…

Thank you for your attention