APS physics VIRTUAL APRIL MEETING
April 18-21, 2020

Tests of Lepton Flavor Universality in Semileptonic $b \to c\ell\nu$ Decays: current results and prospects

Zishuo Yang

University of Maryland / LHCb Collaboration

Supported by NSF

Lepton Flavor Universality (LFU)

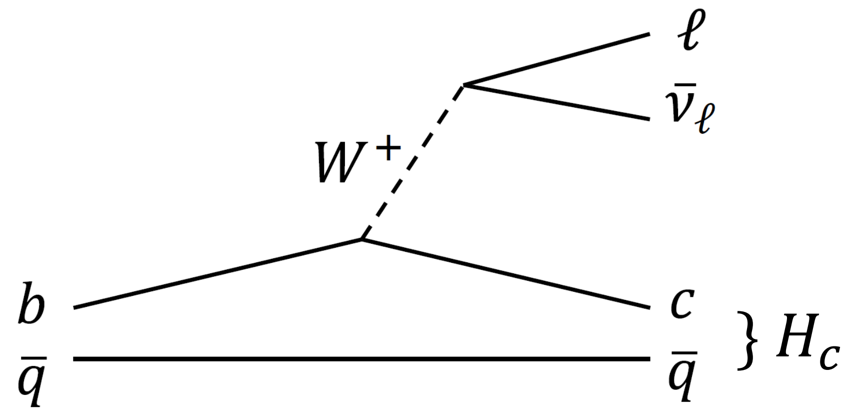
- In Standard Model (SM), charged leptons (e, μ, τ) are identical in terms of their electroweak couplings to gauge bosons
  - only different in their couplings to the Higgs boson (their masses)

- Therefore, difference between decays involving $e/\mu/\tau$ is only due to lepton mass
  - For example: $Z \rightarrow l\, l,\ W \rightarrow l\, \nu, K \rightarrow l\, \nu$, etc.

- *New physics may not necessarily respect LFU*
  - Many new physics models (e.g. charged Higgs, leptoquarks) may involve LFU violation in the 3rd generation

LFU in Semileptonic $b \to c\ell\nu$ Decays

- B hadron decays to lepton, neutrino, and recoiling hadron



- Theoretically well-understood in SM
  - Tree-level virtual W emission
  - Hadronic (nonperturbative) effects described by form factors

- LFU ⇒ branching fractions for semileptonic decays to $e/\mu/\tau$ differ only due to lepton mass (phase space and helicity suppression)

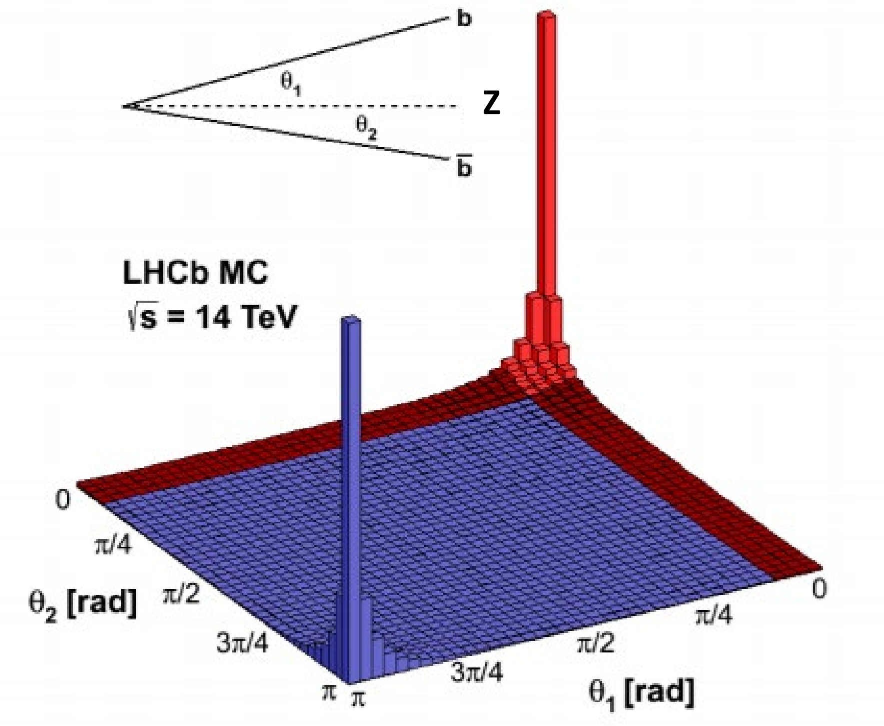
- Test LFU with ratio of branching fractions: $R(H_c) \equiv \dfrac{Br(B\to H_c\,\tau\,\nu)}{Br(B\to H_c\,\mu\,\nu)}$

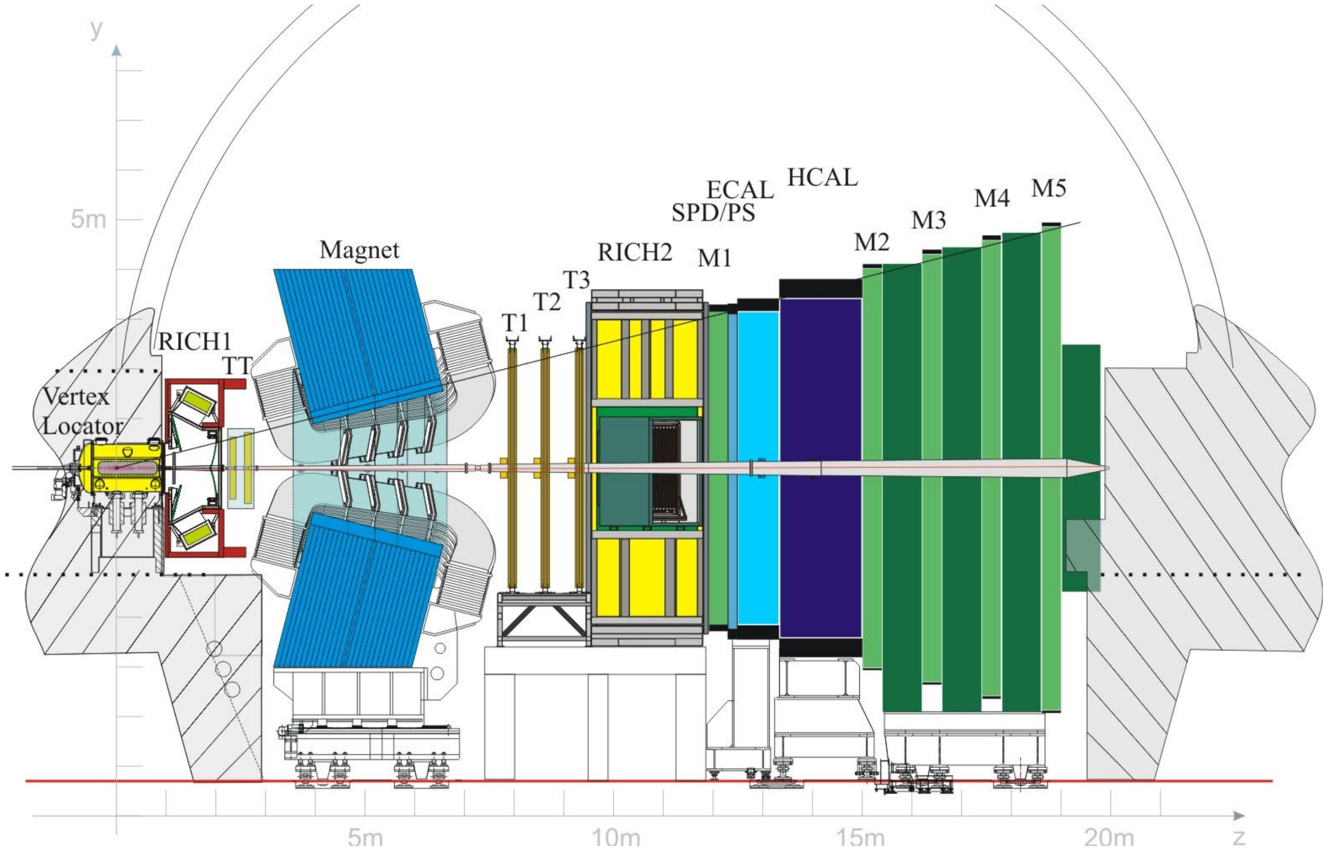
  ✓ Precise theory predictions due to cancellation of most hadronic uncertainties

  ✓ Precise experimental results due to cancellation of some systematic uncertainties

LHCb Detector

- Designed to primarily study heavy flavor physics and CP violation
- Beauty and charm dominantly produced in highly-boosted center-of-mass frame
- Detector accepts 25% of $b\bar{b}$ pairs by covering ~4% of the solid angle ($2 < \eta < 5$)

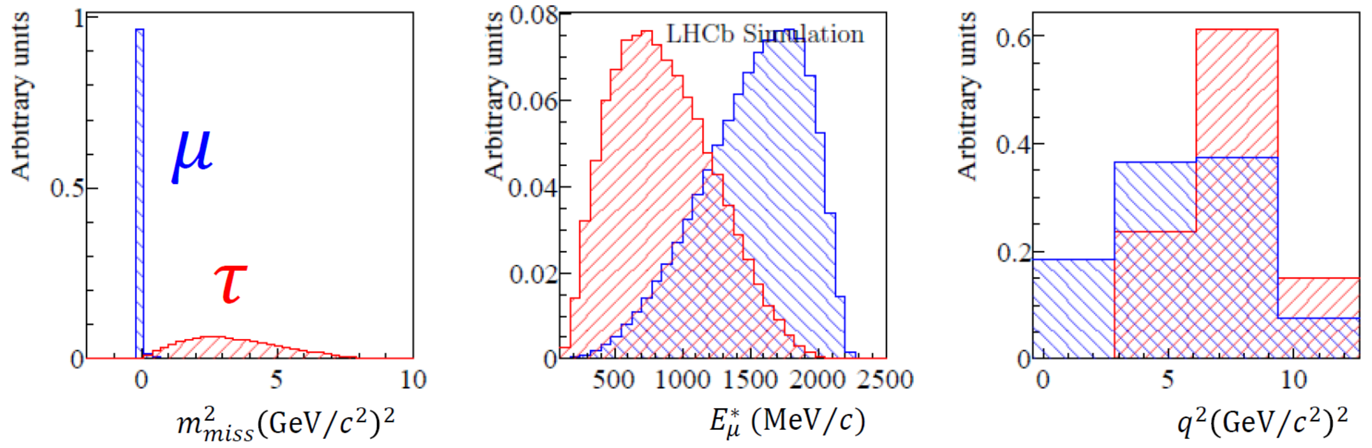


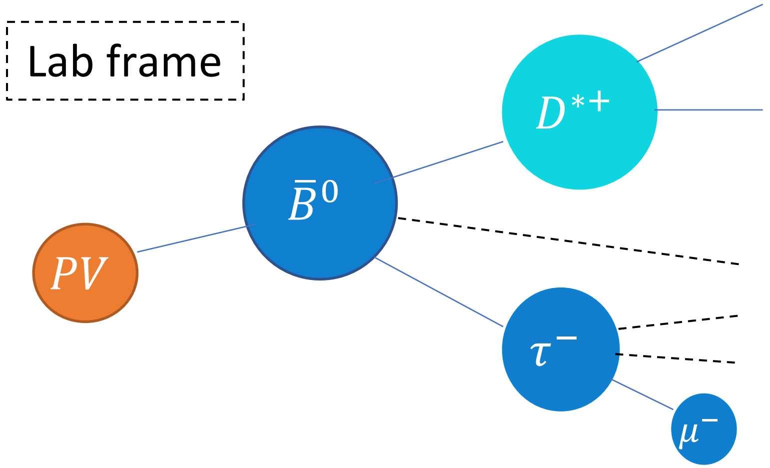


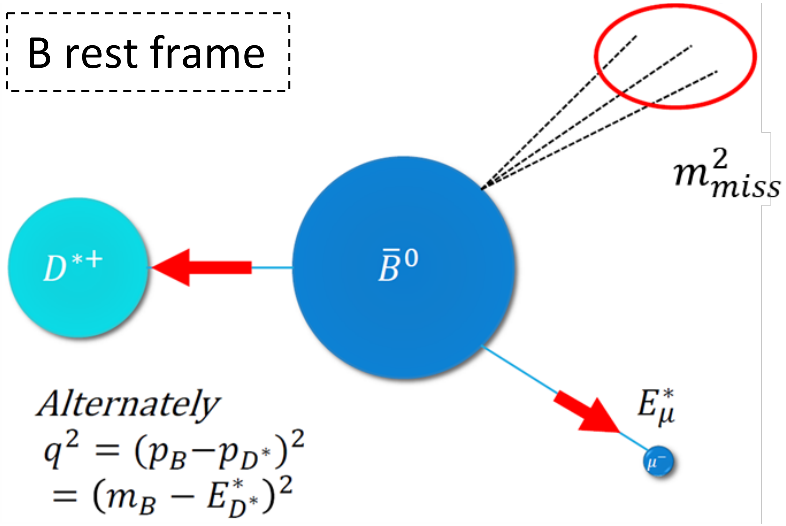
$\sigma_{inel} \approx 70$ mb (13 TeV)
$\sigma_{b\bar{b}} \approx 550$ μb (13 TeV)

$$R(D^*) \equiv \frac{Br(\bar{B}^0 \to D^{*+}\,\tau^-\,\bar{\nu}_\tau)}{Br(\bar{B}^0 \to D^{*+}\,\mu^-\,\bar{\nu}_\mu)}$$ with $\tau \to \mu\bar{\nu}\nu$

- Reconstruct and measure p_l, p_{D^*}, and B flight direction
- Approximate the boost of B system from visible system
- Disentangle signal from normalization using kinematic variables in the rest frame of B:
  - invariant mass of invisible system $m^2{}_{miss}$
  - lepton energy E_l^*
  - momentum transfer $q^2 = m^2{}_{W^*}$



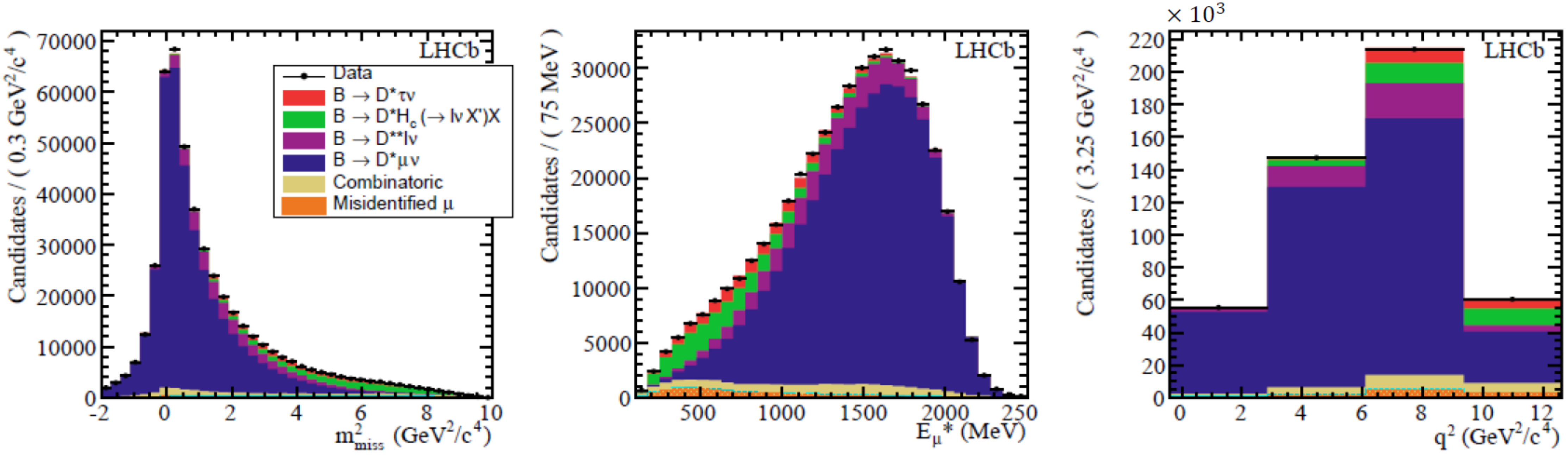




$R(D^*)$ with $\tau \to \mu\bar{\nu}\nu$

PRL 115, 111803 (2015)

- Determine $R(D^*)$ from 3-dimensional fit (m_{miss}^2, E_l^*, q^2)
  - using templates derived from simulation and data control samples

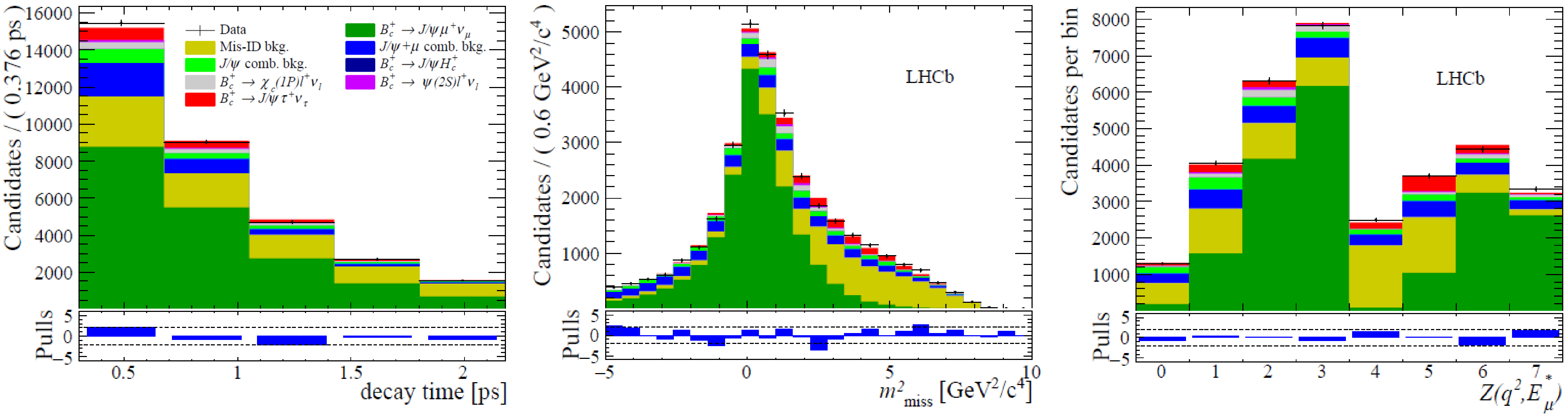


- $R(D^*) = 0.336 \pm 0.027_{stat} \pm 0.030_{syst}$ (about 2.1σ above SM prediction)

$$R(J/\psi) \equiv \frac{Br(B_c^+ \to J/\psi\, \tau^+\, \nu_\tau)}{Br(B_c^+ \to J/\psi\, \mu^+\, \nu_\mu)}$$ with $\tau \to \mu\bar{\nu}\nu$

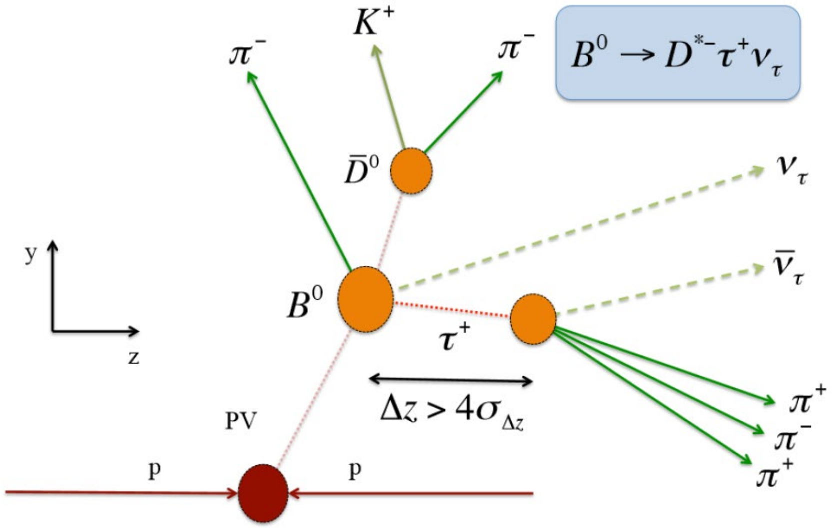
PRL 120, 121801 (2018)

- Similar to $R(D^*)$, but with additional B-candidate decay-time info
  - utilizing 3× difference between lifetimes of B_c and light B hadrons
- Using templates derived from simulation and data control samples
- $R(J/\psi) = 0.71 \pm 0.17_{stat} \pm 0.18_{syst}$ (about 2σ above SM prediction)

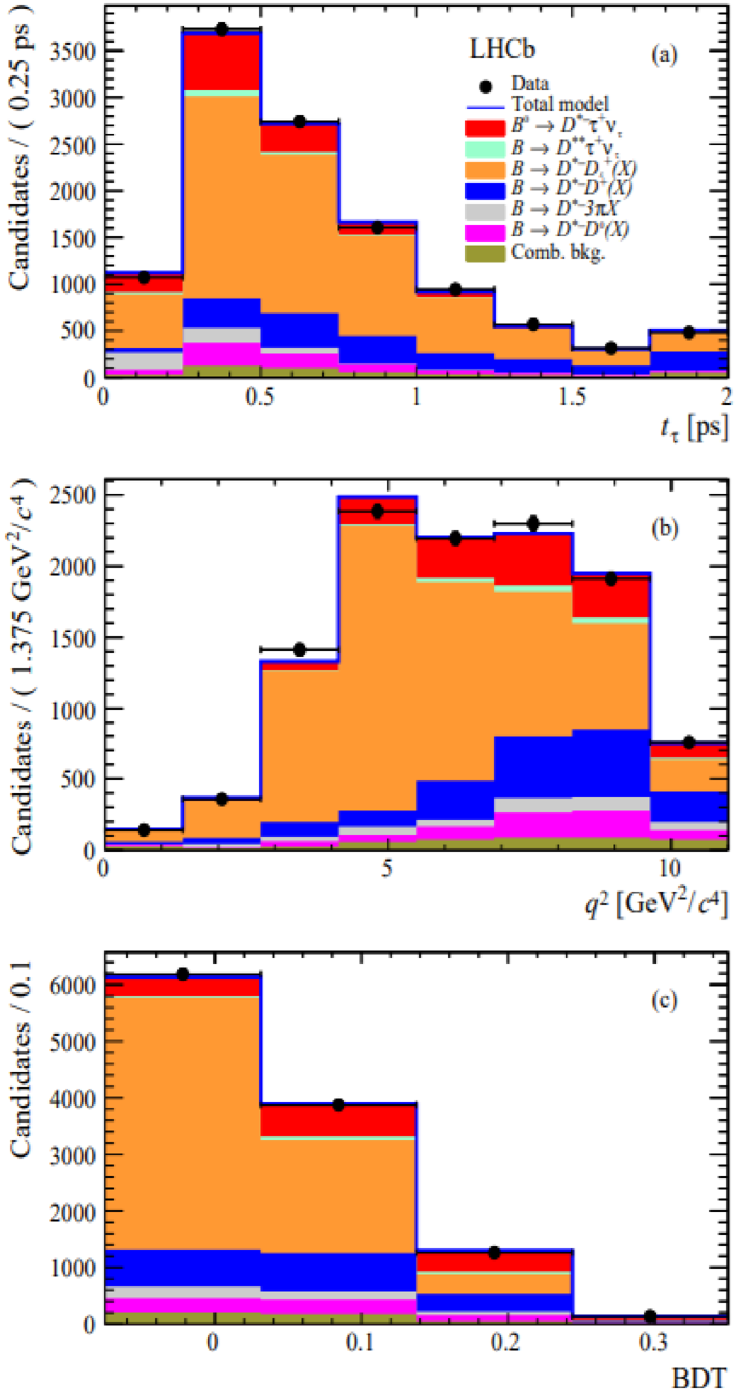


$R(D^*)$ with $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu$

PRD 97, 072013 (2018)

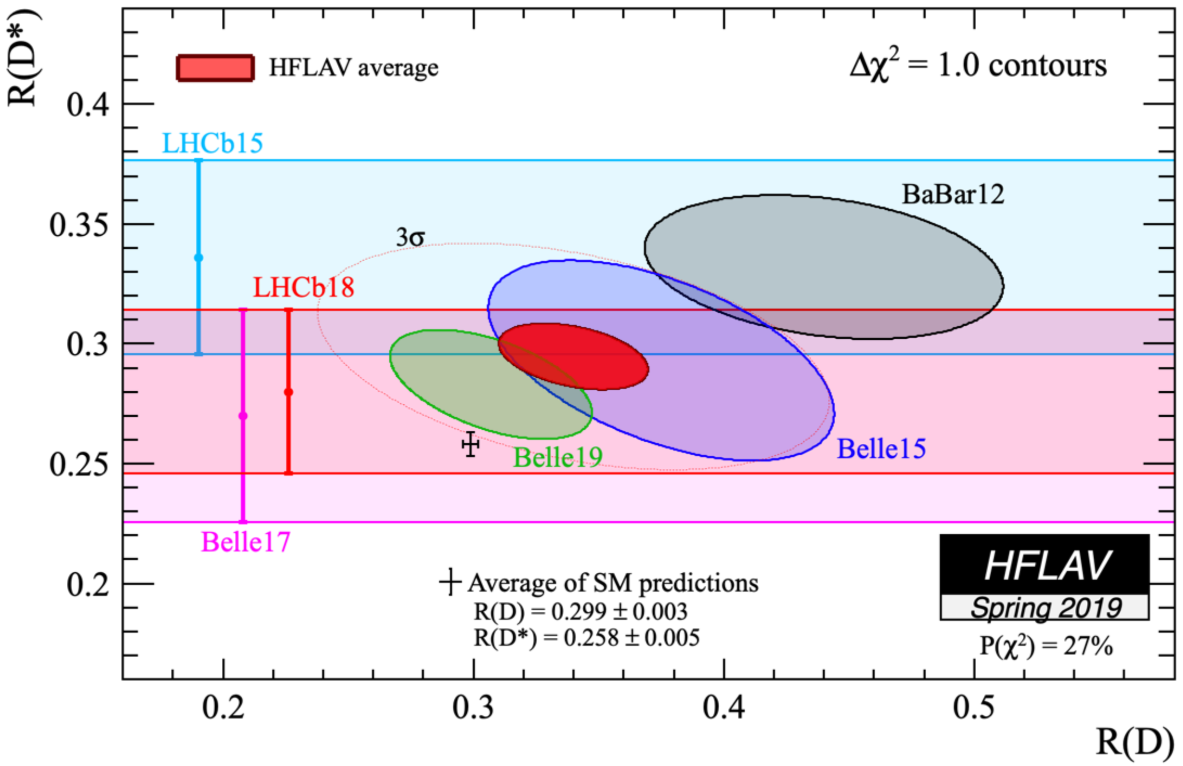


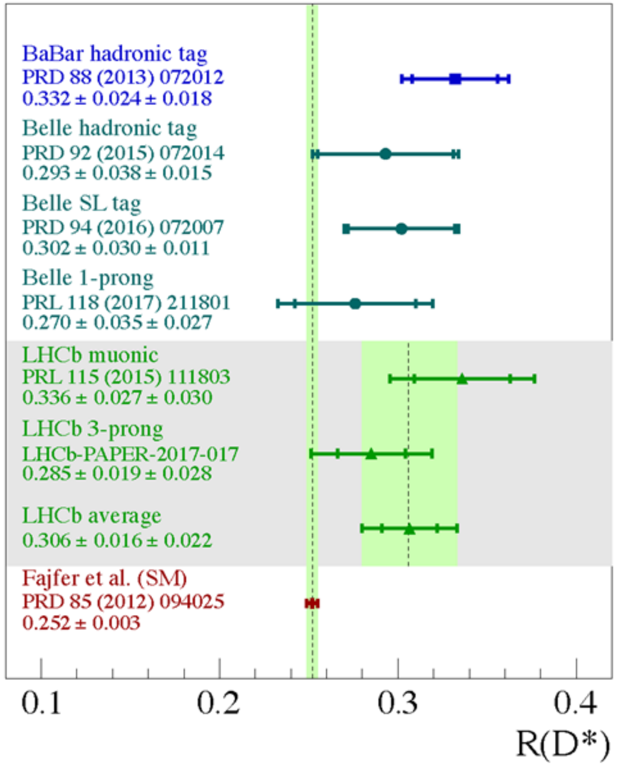
- Reconstruct and measure p_τ, p_{D^*} , B vertex and 3π vertex
- Suppress background by requiring B and 3π vertices separation
- Normalize by $\frac{Br(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{Br(\bar{B}^0 \to D^{*+}3\pi)} \times \frac{Br(\bar{B}^0 \to D^{*+}3\pi)}{Br(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$
- $R(D^*) = 0.291 \pm 0.019_{stat} \pm 0.026_{syst} \pm 0.013_{external}$
  - (1σ above SM prediction)

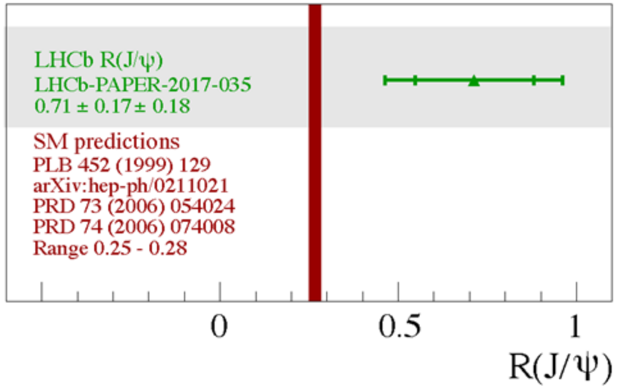


The Global Look

- The tension between world average and SM prediction is at 3.1σ

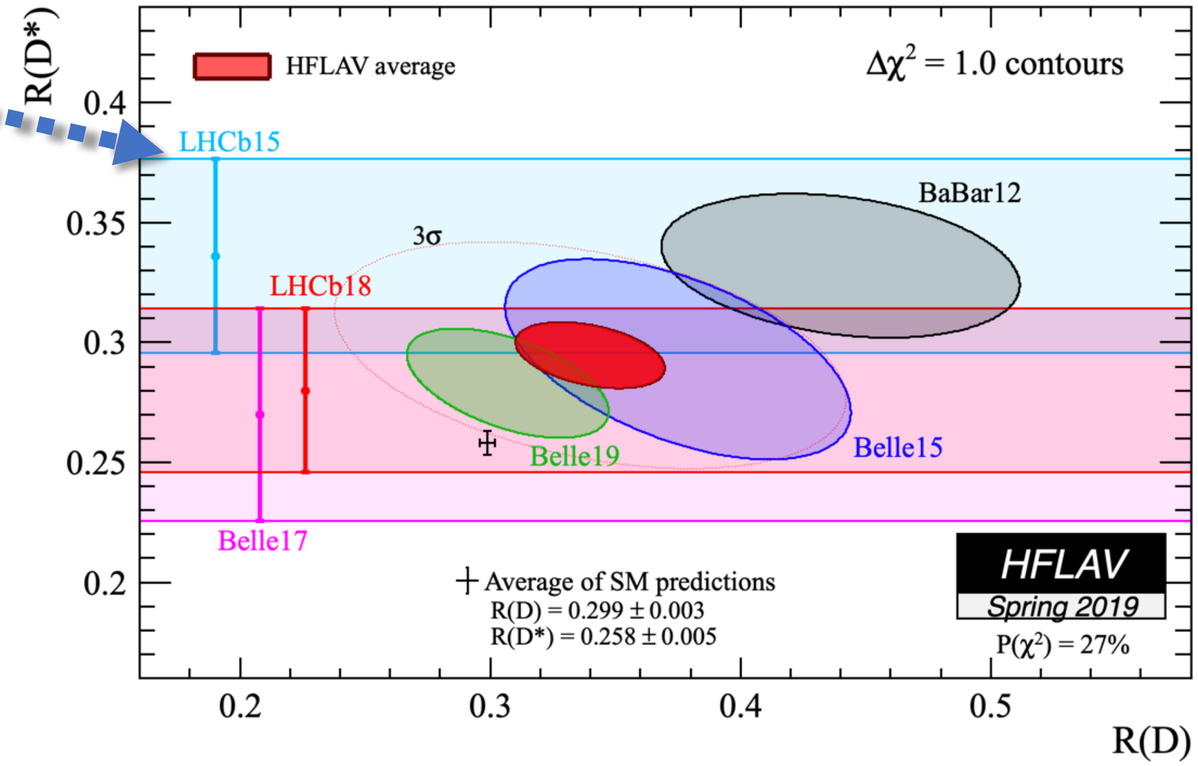






$R(D^*)$ vs $R(D^0)$ with $\tau \to \mu \bar{\nu} \nu$

- LHCb is working to simultaneously measure $R(D^0)$ and $R(D^*)$, “turning band into ellipse”
- Made possible by selecting D^0 + lepton
  - selection includes $B^- \to D^0 l^- \nu, B^0 \to D^{*+} l^- \nu$, and $B^- \to D^{*0}[\to D^0(\pi^0/\gamma)] l^- \nu$
- Significantly improve the statistical power of the measurement
- Hope to complete the analysis this summer



Prospects of LHCb Run-2

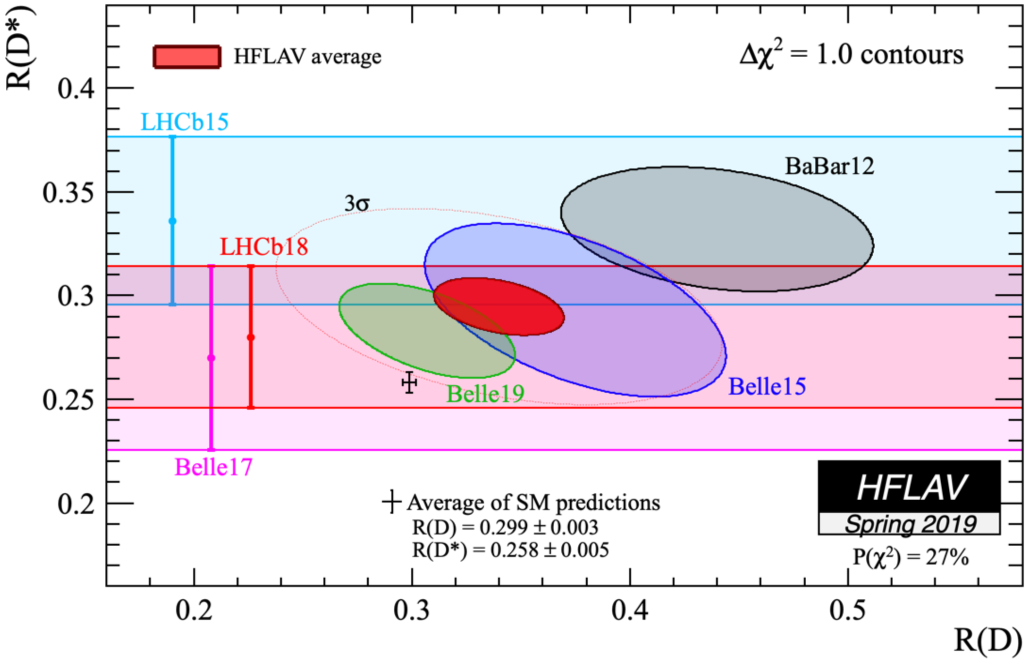
- Expect Run-2 to have 4 times the Run-1 b-hadron statistics
  - $\sim 2\times$ integrated luminosity, and $2\times$ production cross section

- Added triggers for $D^0\mu, D^+\mu, D_s\mu$, and $\Lambda_c^+\mu$

- Many analyses are ongoing: $R(D^0), R(D^*), R(D^+), R(D_s), R(\Lambda_c^+), R(\Lambda_c^{*+})$ and $R(J/\psi)$

Summary

- Current measurements of semileptonic B decays indicate hints of τ/μ non-universality



- Many new measurements to come soon

- LHCb has a comprehensive program to perform precise LFU tests, with current data as well as anticipated (much larger) dataset from the upgraded LHCb detector

Backup slides

Systematic Uncertainties: $R(D^*)$ Muonic

TABLE I. Systematic uncertainties in the extraction of $\mathcal{R}(D^*)$.

Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\bar{B}^0 \to D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors	0.6
$\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{**}\mu^-\bar{\nu}_\mu)$	0.5
$\bar{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\bar{B} \to D^{**}(\to D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors	0.3
$\bar{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

PRL 115, 111803 (2015)

Systematic Uncertainties: $R(J/\psi)$ Muonic

TABLE I. Systematic uncertainties in the determination of $\mathcal{R}(J/\psi)$.

Source of uncertainty	Size ($\times 10^{-2}$)
Finite simulation size	8.0
$B_c^+ \to J/\psi$ form factors	12.1
$B_c^+ \to \psi(2S)$ form factors	3.2
Fit bias correction	5.4
Z binning strategy	5.6
Mis-ID background strategy	5.6
combinatorial background cocktail	4.5
combinatorial J/ψ background scaling	0.9
$B_c^+ \to J/\psi H_c X$ contribution	3.6
$\psi(2S)$ and χ_c feed-down	0.9
Weighting of simulation samples	1.6
Efficiency ratio	0.6
$\mathcal{B}(\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau)$	0.2
Systematic uncertainty	17.7
Statistical uncertainty	17.3

PRL 120, 121801 (2018)

Systematic Uncertainties: $R(D^*)$ Hadronic

TABLE VII. List of the individual systematic uncertainties for the measurement of the ratio $\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)/\mathcal{B}(B^0 \to D^{*-}3\pi)$.

Contribution	Value in %
$\mathcal{B}(\tau^+ \to 3\pi\bar{\nu}_\tau)/\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\bar{\nu}_\tau)$	0.7
Form factors (template shapes)	0.7
Form factors (efficiency)	1.0
τ polarization effects	0.4
Other τ decays	1.0
$B \to D^{**}\tau^+\nu_\tau$	2.3
$B_s^0 \to D_s^{**}\tau^+\nu_\tau$ feed-down	1.5
$D_s^+ \to 3\pi X$ decay model	2.5
D_s^+, D^0 and D^+ template shape	2.9
$B \to D^{*-}D_s^+(X)$ and $B \to D^{*-}D^0(X)$ decay model	2.6
$D^{*-}3\pi X$ from B decays	2.8
Combinatorial background (shape + normalization)	0.7
Bias due to empty bins in templates	1.3
Size of simulation samples	4.1
Trigger acceptance	1.2
Trigger efficiency	1.0
Online selection	2.0
Offline selection	2.0
Charged-isolation algorithm	1.0
Particle identification	1.3
Normalization channel	1.0
Signal efficiencies (size of simulation samples)	1.7
Normalization channel efficiency (size of simulation samples)	1.6
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0
Total uncertainty	9.1

PRD 97, 072013 (2018)