

Tests of Lepton-flavour universality and related anomalies at LHCb

Quarks 2018, Valday

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On behalf of LHCb collaboration



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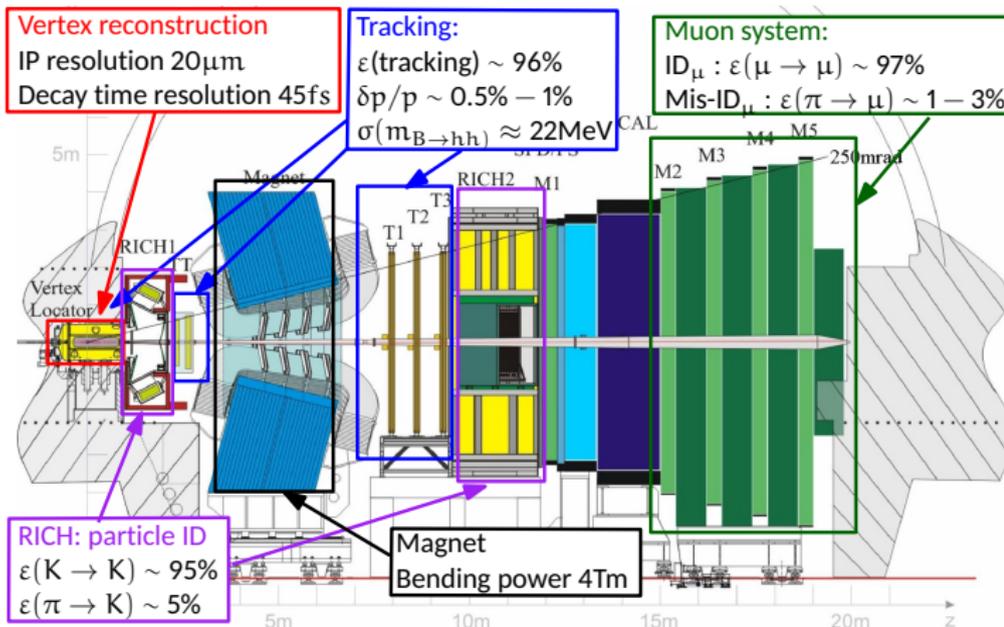
Introduction

LHCb detector

Overview

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

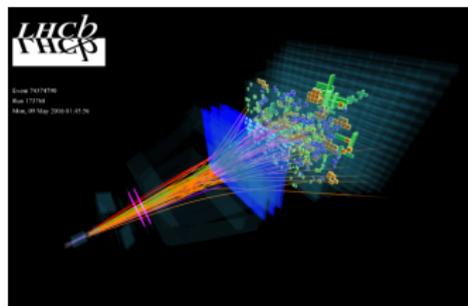
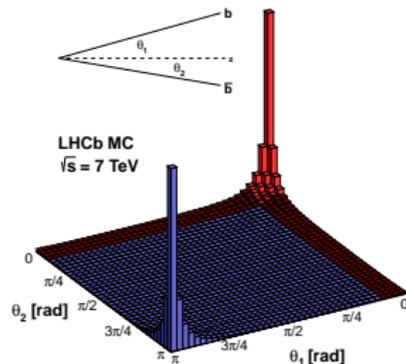
- Single-arm forward spectrometer $\eta \in [2; 5]$



LHCb detector

B decays in LHCb

- Large amount of Data
 - Run 1 (2011, 2012): 3fb^{-1} at 7 – 8TeV
 - Run 2 (2015- 2018): 4.1fb^{-1} at 13TeV (still ongoing)
- B-mesons production:
 - $\sigma(b\bar{b})_{7\text{TeV}} = 75\mu\text{b}$ in acceptance [PLB 694 (2010) 209-216]
 - $2.3 \times 10^{+9} b\bar{b}$ pairs produced in Run 1
- Rich B decay channels
- Secondary vertex reconstruction
- Challenges
 - Unknown B-meson momentum
 - Non clean environment



Lepton flavour universality in SM

Lepton Flavour Universality

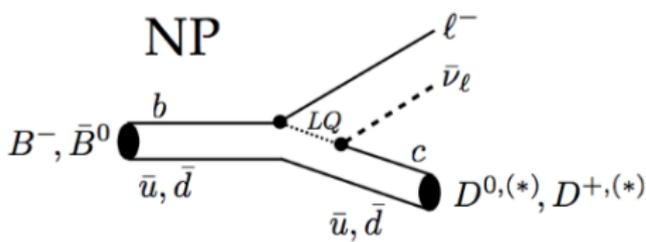
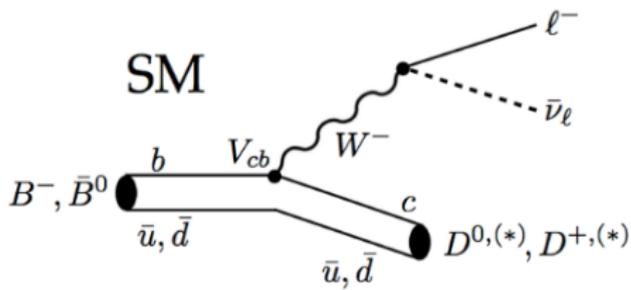
3 lepton families have same coupling to gauge bosons:

$$g_e = g_\mu = g_\tau$$

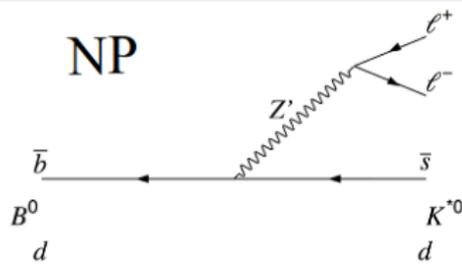
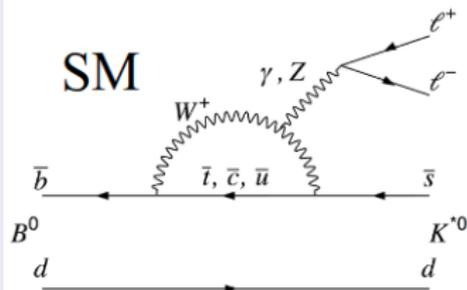
- Difference in BR only from difference in masses
- NP particles may couple to leptons differently
 - Leptoquarks, charged Higgs, Z' , SuSy, hidden valley etc.

Lepton flavour universality in SM

Tree level $b \rightarrow cl\nu$



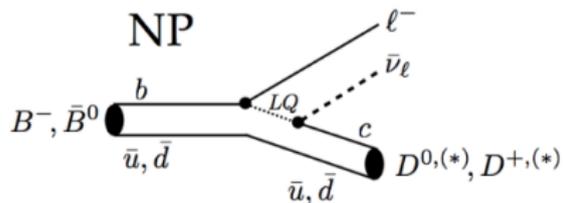
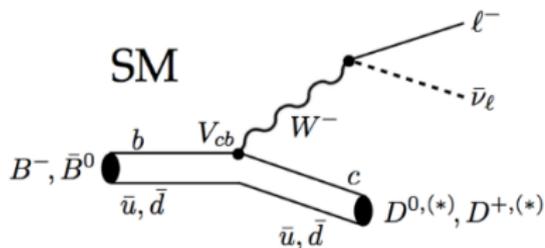
FCNC $b \rightarrow sll$



LFU in $b \rightarrow c l \nu$ decay

Tree-level $b \rightarrow cl\nu$ decays

Ratio of branching fractions τ/μ



Ratio of branching fractions $R(H_c)$

$$R(H_c) = \frac{\mathcal{BR}(B \rightarrow H_c \tau \nu)}{\mathcal{BR}(B \rightarrow H_c \mu \nu)}$$

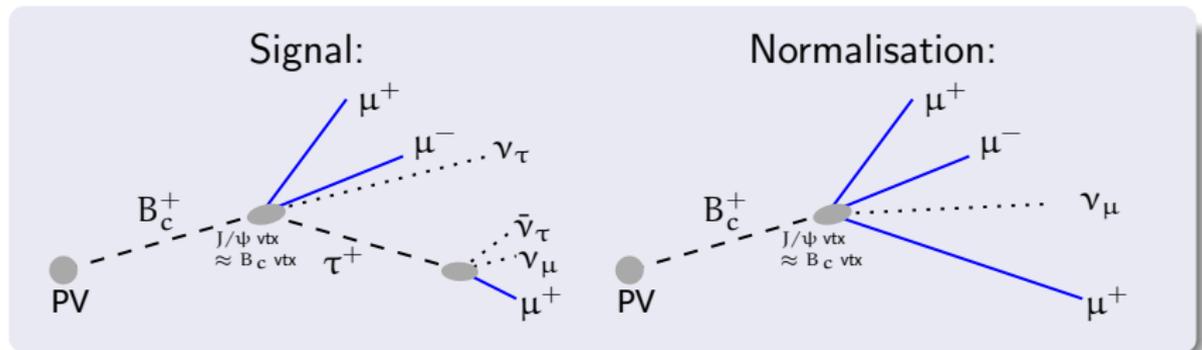
- Cancels hadronic and experimental systematics

Leptonic tau decay

 $R(J/\psi)$ with leptonic tau decay

[PRL 120 (2018) 121801]

$$R(J/\psi) = \frac{\mathcal{BR}(B_c \rightarrow J/\psi \tau \nu)}{\mathcal{BR}(B_c \rightarrow J/\psi \mu \nu)}$$



- B_c short decay time: helps discriminate BG from other B
- B_c reconstructed using flight vector and $(J/\psi, \mu)$ system
- 3 muons in final state
 - Background dominated by:
 - MisID, $J/\psi + \mu$ combinatorial

$R(J/\psi)$ with leptonic tau decay

[PRL 120 (2018) 121801]

 $B_c \rightarrow J/\psi l \nu$ form factors

- Only theoretical predictions exists
 - Kiselev [arXiv:hep-ph/0211021]
 - Ebert, Faustov, and Galkin [PRD 68 (2003) 094020]
 - Hernandez, Nieves, Verde-Velasco [PRD 74 (2006) 074008]
 - Wang, Shen and Lu [PRD 79 (2009) 054012]
- $R(J/\psi)_{\text{SM}} = 0.25 - 0.28$

FF determination in $R(J/\psi)$

- In $B_c \rightarrow J/\psi \mu$ rich region
 - By fit estimate $A_1(q^2), A_2(q^2), V(q^2)$ (following EFG convention)
- In the nominal fit
 - $A_{1,2}, V$ fixed
 - A_0 unconstrained

Leptonic tau decay

 $R(J/\psi)$ with leptonic tau decay

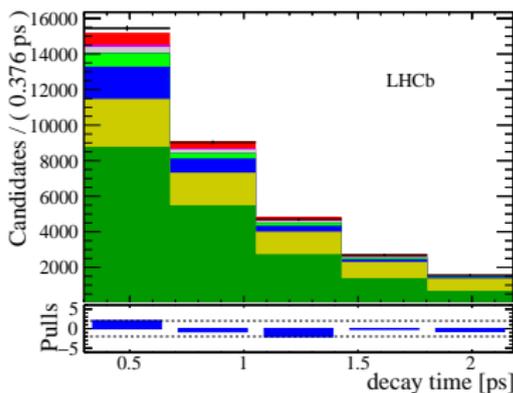
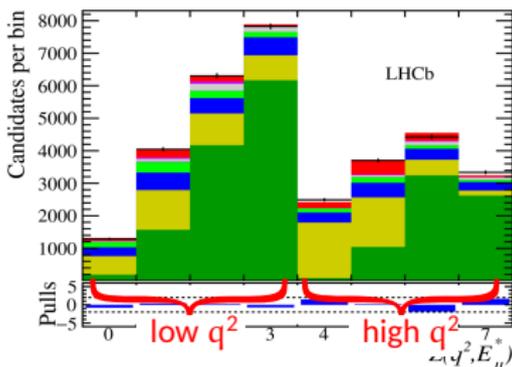
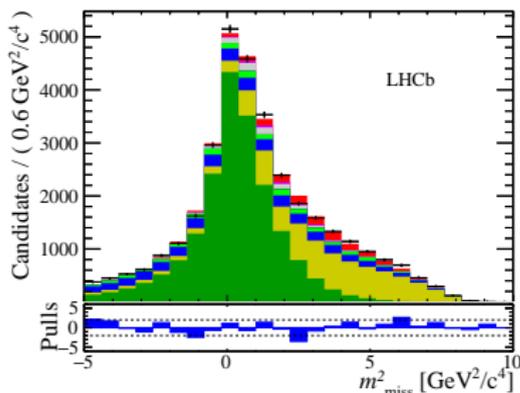
[PRL 120 (2018) 121801]

3D template fit (m_{miss}^2, B_c decay time, Z)

- 3D template fit:

$$m_{\text{miss}}^2, B_c \text{ decay time}, Z = (q^2, E_\mu^*)$$

- Using Run 1 data (3fb^{-1})



$R(J/\psi)$ with leptonic tau decay

[PRL 120 (2018) 121801]

Results

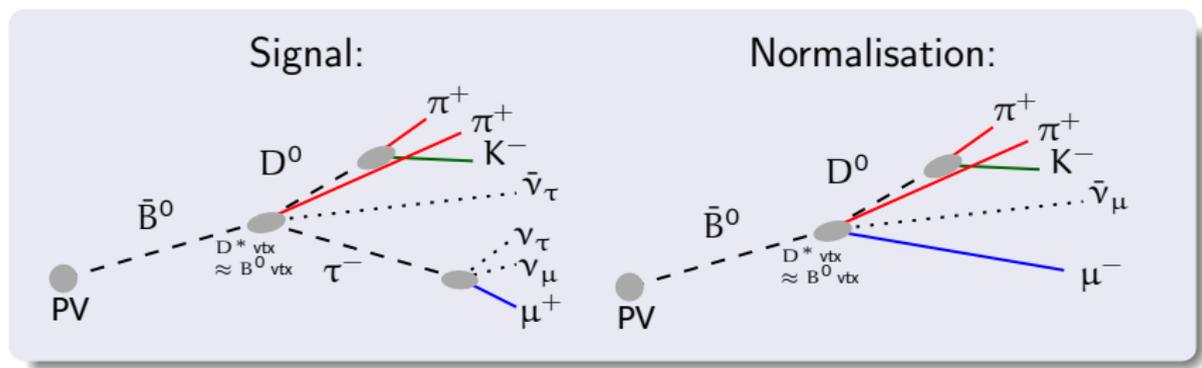
Fit result

- $R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$
- Dominant systematics: $B_c \rightarrow (c\bar{c})l\nu$ FF
- $R(J/\psi)_{\text{SM}} = 0.25 - 0.28$
- 2σ deviation
- First result of $R(J/\psi)$

$R(D^*)$ with leptonic tau decay

[PRL 115 (2015) 111803]

$$R(D^*) = \frac{\mathcal{BR}(B^0 \rightarrow D^* \tau \nu)}{\mathcal{BR}(B^0 \rightarrow D^* \mu \nu)}$$



- Same visible end-state for signal and normalisation
- B^0 reconstructed using flight vector and

$$(p_B)_z = \frac{m_B}{m_{\text{reco}}} (p_{\text{reco}})_z$$
- Dominant backgrounds:

$$B \rightarrow D^* H_c (\rightarrow l \nu X) X, \text{ combinatorial}$$

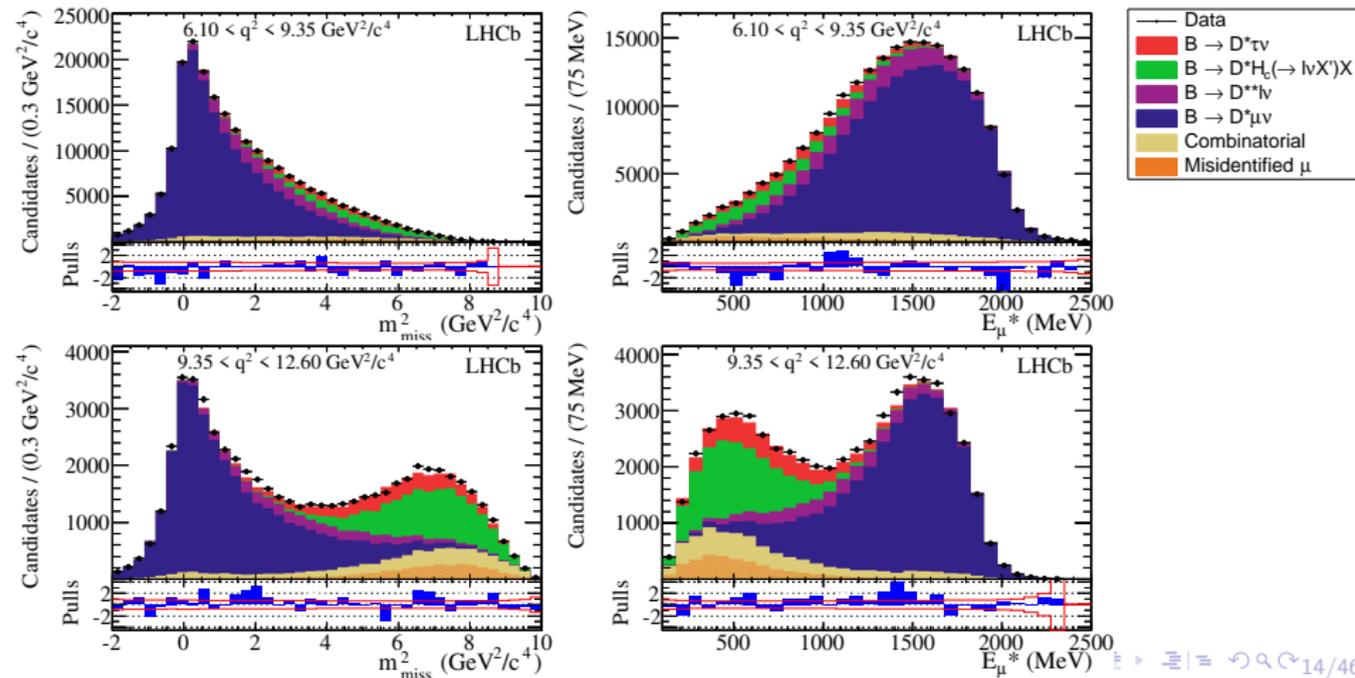
Leptonic tau decay

 $R(D^*)$ with leptonic tau decay

[PRL 115 (2015) 111803]

Template fit

- 3D template fit: $m_{\text{miss}}^2, E_{\mu}^*, q^2$
- Using Run 1 data (3fb^{-1})



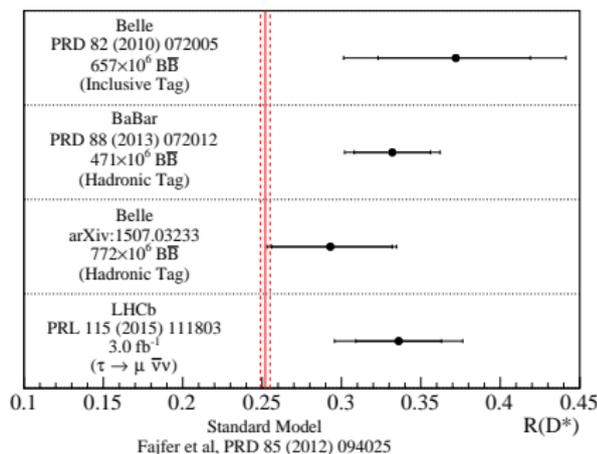
$R(D^*)$ with leptonic tau decay

[PRL 115 (2015) 111803]

Results

Fit result

- $R(D^*) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$
- Dominant systematic: sim sample size
- $R(D^*)_{\text{SM}} = 0.252 \pm 0.003$
[PRD 85 (2012) 094025]
- **2.1 σ** deviation



Hadronic tau decay

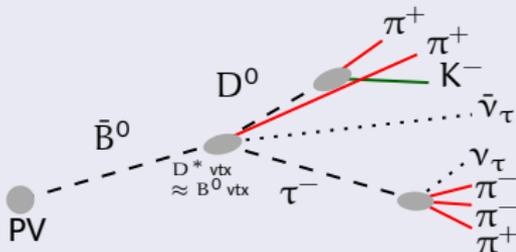
 $R(D^*)$ with hadronic tau decay

[PRD 97 (2018) 072013]

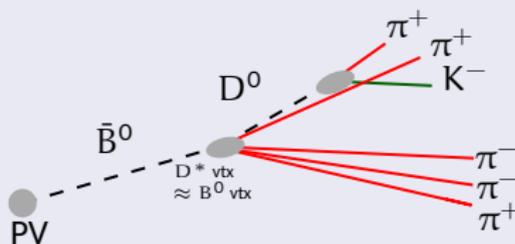
$$R(D^*) = \frac{\mathcal{BR}(B^0 \rightarrow D^* \tau \nu)}{\mathcal{BR}(B^0 \rightarrow D^* 3\pi)} \times \frac{\mathcal{BR}(B^0 \rightarrow D^* 3\pi)}{\mathcal{BR}(B^0 \rightarrow D^* \mu \nu)}$$

[PRL 120 (2018) 171802]

Signal:



Normalisation:

Normalisation decay $B^0 \rightarrow D^* 3\pi$

- $R(D^*) = \frac{\mathcal{BR}(B^0 \rightarrow D^* \tau \nu)}{\mathcal{BR}(B^0 \rightarrow D^* 3\pi)} \times \frac{\mathcal{BR}(B^0 \rightarrow D^* 3\pi)}{\mathcal{BR}(B^0 \rightarrow D^* \mu \nu)}$
- with known
 - $\mathcal{BR}(B^0 \rightarrow D^* 3\pi) = (7.214 \pm 0.28) \times 10^{-3}$
 - $\mathcal{BR}(B^0 \rightarrow D^* \mu) = (4.88 \pm 0.11)\%$ [EPJC 77 (2017) 895]

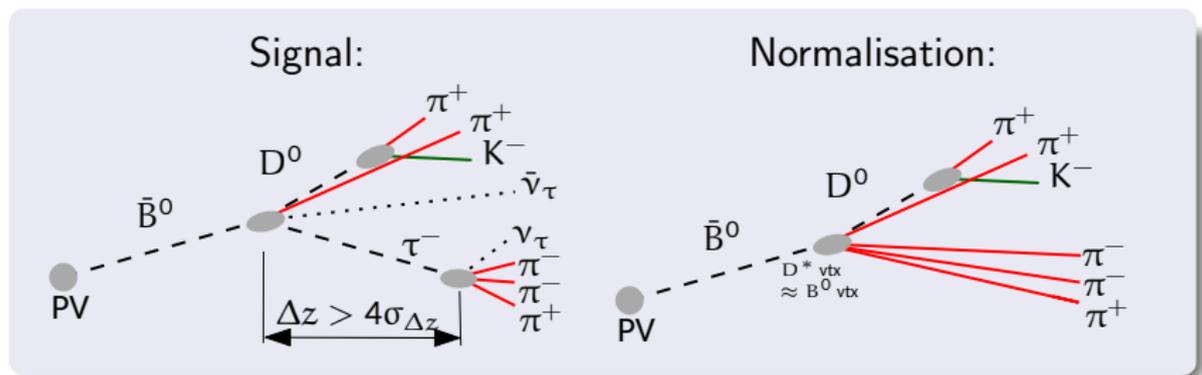
Hadronic tau decay

 $R(D^*)$ with hadronic tau decay

$$R(D^*) = \frac{\mathcal{BR}(B^0 \rightarrow D^* \tau \nu)}{\mathcal{BR}(B^0 \rightarrow D^* 3\pi)} \times \frac{\mathcal{BR}(B^0 \rightarrow D^* 3\pi)}{\mathcal{BR}(B^0 \rightarrow D^* \mu \nu)}$$

[PRD 97 (2018) 072013]

[PRL 120 (2018) 171802]



- B_0 and τ reconstructible with mass hypothesis
- Huge and complex background dominated by
 - $B \rightarrow D^{*-} 3\pi X$ – Detached τ vertex
 - $B \rightarrow D^{*-} D_s X$ – Isolated τ vertex

Hadronic tau decay

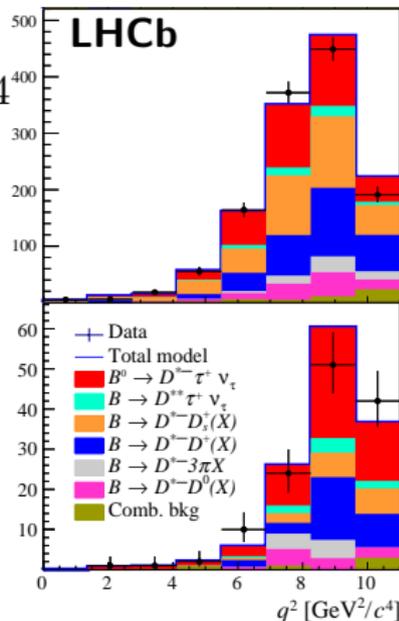
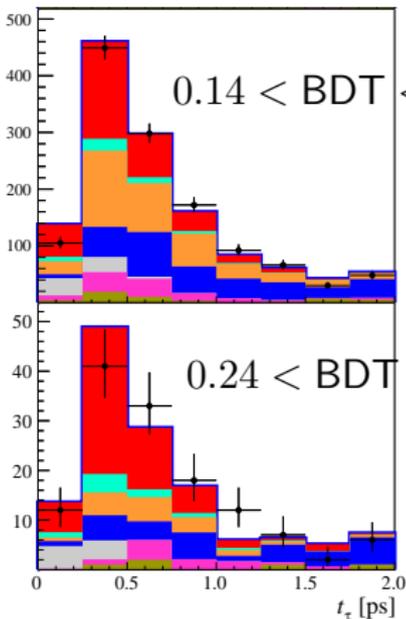
 $R(D^*)$ with hadronic tau decay

Template fit

[PRD 97 (2018) 072013]

[PRL 120 (2018) 171802]

- 3D template fit:
 τ decay time, q^2 , BDT = (Isolation, E_{τ} , m_{B_0} etc.)
- Using Run 1 data (3fb^{-1})



Hadronic tau decay

 $R(D^*)$ with hadronic tau decay

Results

[PRD 97 (2018) 072013]

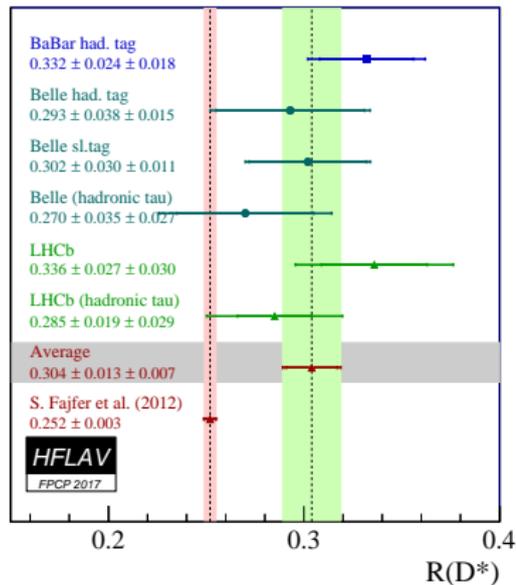
[PRL 120 (2018) 171802]

Fit result

- $R(D^*) = 0.291 \pm 0.019(\text{stat}) \pm 0.026(\text{syst}) \pm 0.013(\text{ext})$
- Dominant systematics: sim sample size
- $R(D^*)_{\text{SM}} = 0.252 \pm 0.003$
[PRD 85 (2012) 094025]
- 1.1σ deviation

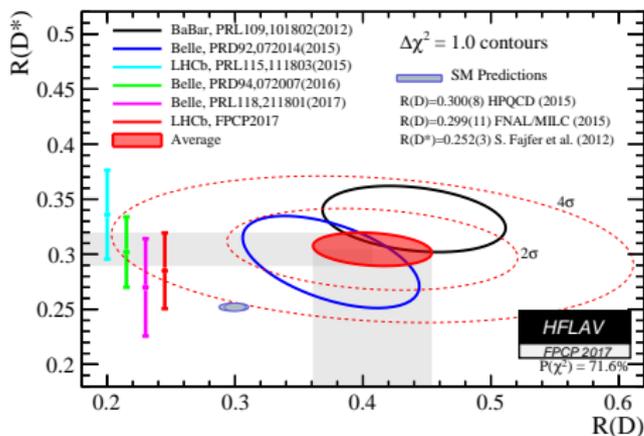
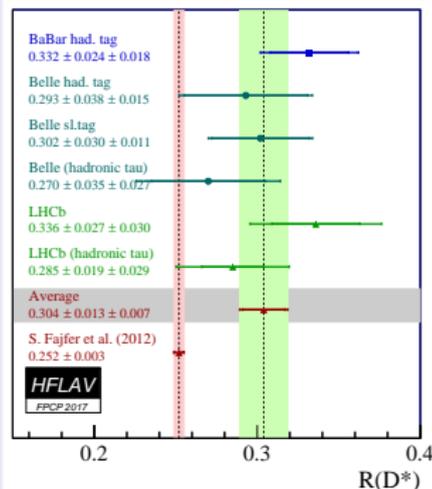
LHCb average

- $R(D^*) = 0.310 \pm 0.016(\text{stat}) \pm 0.022(\text{syst})$
- 2.2σ deviation



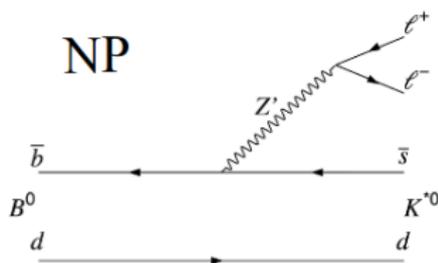
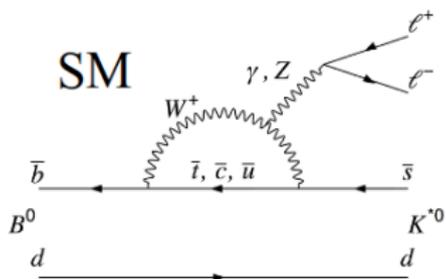
Summary for $b \rightarrow cl\nu$

[HFLAV FPCP17]

 $R(D) - R(D^*)$ combined $R(D^*)$ combined

- Combined $R(D^*)$ deviates by 3.5σ from SM
- Combined $R(D), R(D^*)$ deviates by 4.1σ from SM
- $R(J/\psi)$ deviates by 2.1σ from SM

LFU in $b \rightarrow sll$ FCNC decay

FCNC $b \rightarrow s l l$ transition

- Forbidden at tree level: rare decays

Ratio of branching ratios $R(H_s)$

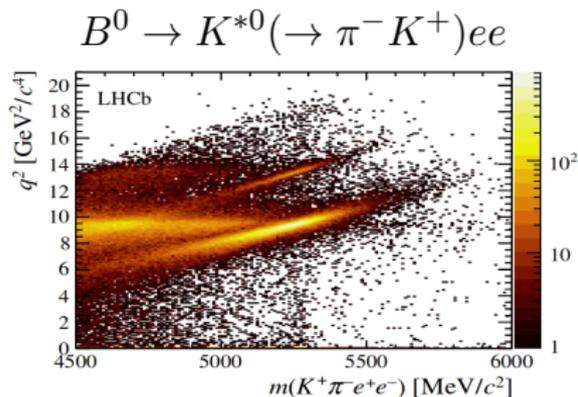
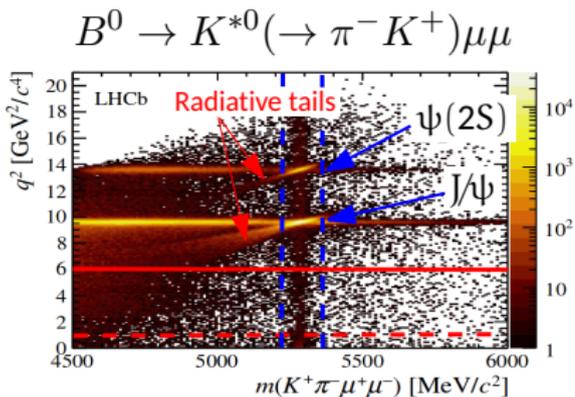
$$R(H_s) = \frac{\mathcal{BR}(B \rightarrow H_s \mu \mu)}{\mathcal{BR}(B \rightarrow H_s e e)} = \frac{\mathcal{BR}(B \rightarrow H_s \mu \mu)}{\mathcal{BR}(B \rightarrow H_s J/\psi (\rightarrow \mu \mu))} \frac{\mathcal{BR}(B \rightarrow H_s J/\psi (\rightarrow e e))}{\mathcal{BR}(B \rightarrow H_s e e)}$$

- Useful to measure via double ratio w.r.t. $B \rightarrow H_s J/\psi$
 $\mathcal{BR}(J/\psi \rightarrow \mu \mu) / \mathcal{BR}(J/\psi \rightarrow e e)$ consistent with LFU [PDG]
- $R(H_s)_{\text{SM}} = 1 + \mathcal{O}(10^{-3})$

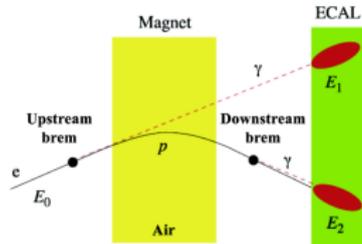
$R(K^*)$

[JHEP 08 (2017) 055]

$$R(K^*) = \frac{\mathcal{BR}(B^0 \rightarrow K^{*0} \mu \mu)}{\mathcal{BR}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu \mu))} \frac{\mathcal{BR}(B^0 \rightarrow K^{*0} J/\psi (\rightarrow ee))}{\mathcal{BR}(B^0 \rightarrow K^{*0} ee)}$$



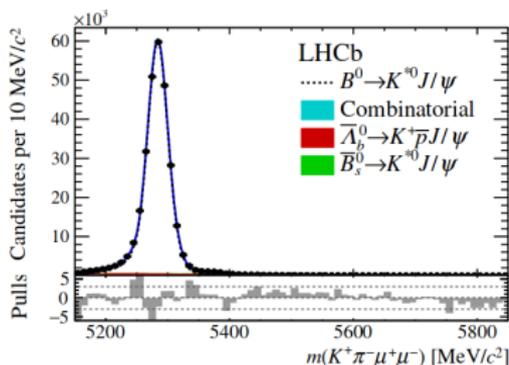
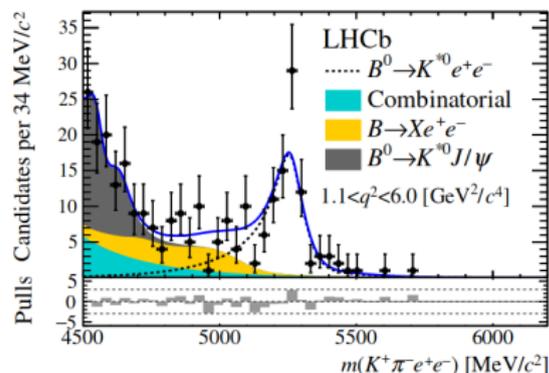
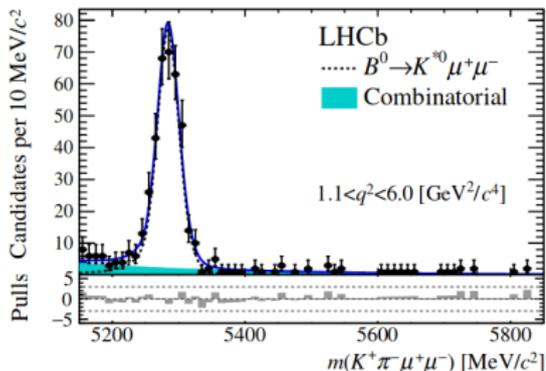
- $q^2 = m^2(ll)$
 - Low q^2 : $[0.044, 1.1] \text{GeV}^2$
 - Central q^2 : $[1.1, 6] \text{GeV}^2$
- Challenging e reconstruction
 - Bremsstrahlung radiation



$R(K^*)$

Fit of $m(K\pi ll)$

[JHEP 08 (2017) 055]



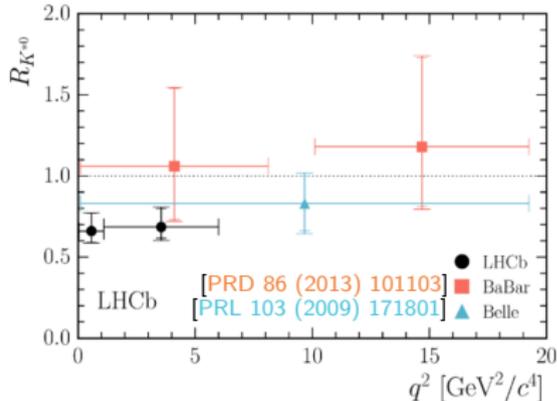
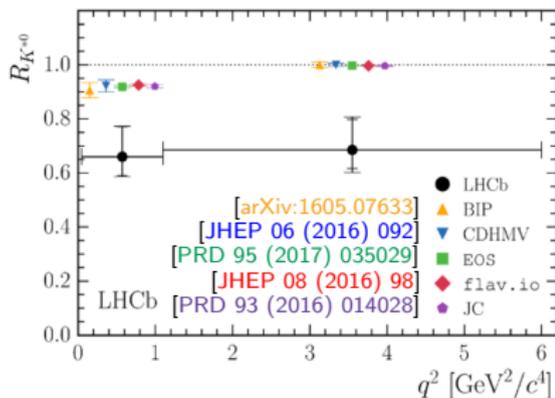
$R(K^*)$

Fit results

[JHEP 08 (2017) 055]

Fit results

q^2 bin	$R(K^*)$	$R(K^*)_{SM}$	Deviation
[0.045, 1.1]	$0.66^{+0.11}_{-0.07}(\text{stat}) \pm 0.03(\text{syst})$	$0.92 + \mathcal{O}(10^{-3})$	$2.1 - 2.3\sigma$
[1.1, 6.0]	$0.69^{+0.11}_{-0.07}(\text{stat}) \pm 0.05(\text{syst})$	$0.99 + \mathcal{O}(10^{-3})$	$2.4 - 2.5\sigma$



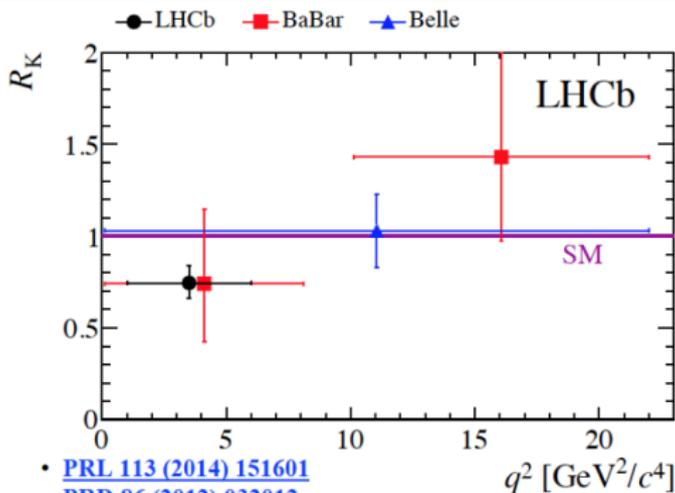
$R(K)$

[PRL 113 (2014) 151601]

$$R(K) = \frac{\mathcal{BR}(B^+ \rightarrow K^+ \mu \mu)}{\mathcal{BR}(B^+ \rightarrow K^+ J/\psi (\rightarrow \mu \mu))} \frac{\mathcal{BR}(B^+ \rightarrow K^+ J/\psi (\rightarrow ee))}{\mathcal{BR}(B^+ \rightarrow K^+ ee)}$$

Fit results

q^2 bin	$R(K^+)$	$R(K^+)_{\text{SM}}$	Deviation
[1.0, 6.0]	$0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$	$0.99 + \mathcal{O}(10^{-3})$	2.6σ



- [PRL 113 \(2014\) 151601](#)
- [PRD 86 \(2012\) 032012](#)
- [PRL 103 \(2009\) 171801](#)

$R(K)/R(K^*)$ combined

[PRD 96 (2017) 055008]

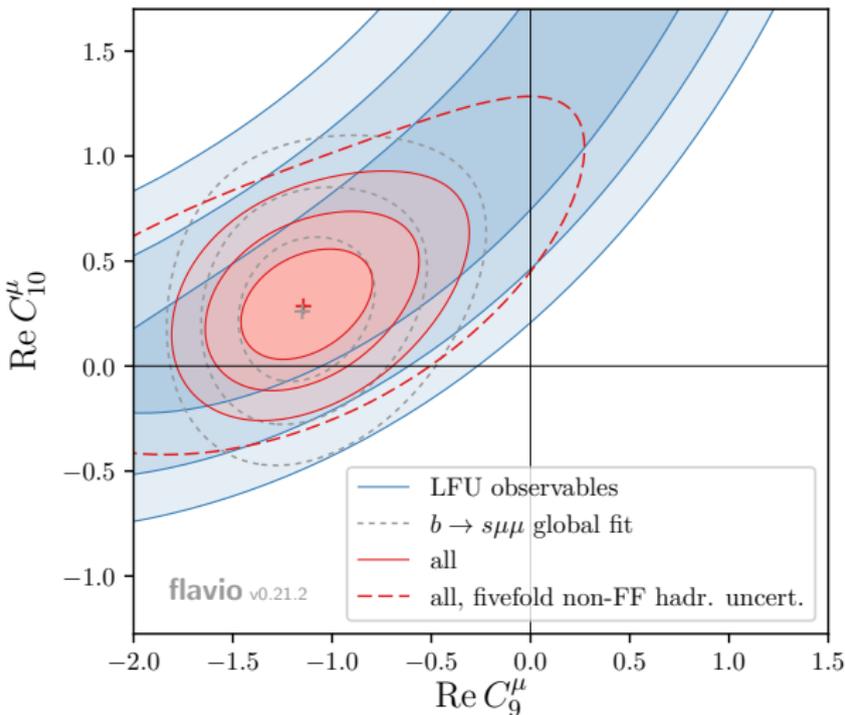
Wilson coeff. $C_i^{(\nu)l}$

$$\mathcal{H}_{\text{eff}}^{\text{NP}} \propto \sum_{i,l} C_i^l O_l^i + C_i^{ll} O_l^{ii}$$

$$O_9^l = (\bar{s}\gamma_\nu P_L b)(\bar{l}\gamma^\nu l)$$

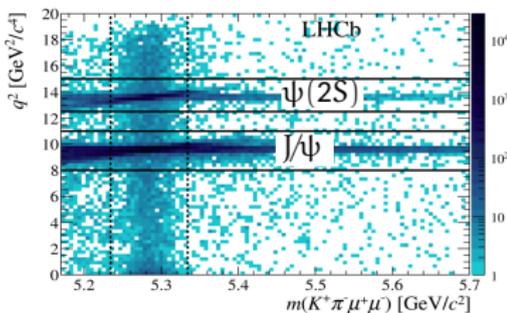
$$O_{10}^l = (\bar{s}\gamma_\nu P_L b)(\bar{l}\gamma^\nu \gamma_5 l)$$

- $R(K)/R(K^*)$
combined with Belle
[arXiv:1612.05014]
 - $> 4\sigma$ deviation

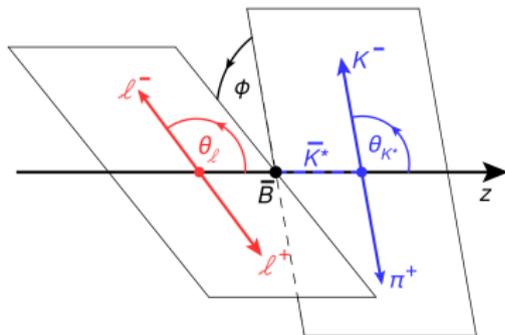


Anomalies in $b \rightarrow s l l$ $B^0 \rightarrow K^{*0} \mu \mu$ angular analysis

[JHEP 02 (2016) 104]



$$q^2 = m(\mu\mu)$$



$$\vec{\Omega} = (\cos \theta_l, \cos \theta_K, \phi)$$

CP-averaged partial width

$$\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\vec{\Omega}} = \frac{9}{39\pi} \sum_i S_i f_i(\vec{\Omega})$$

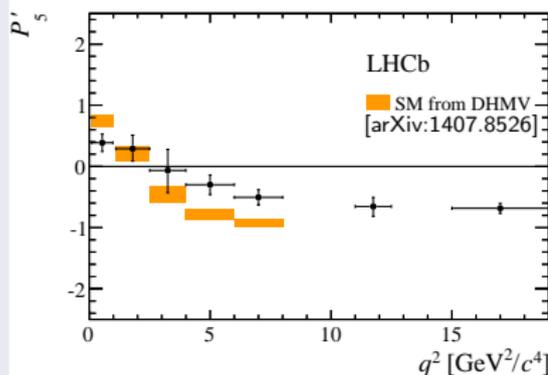
- 8 $S_i(q^2; C_{7,9,10}, \text{FF})$ observables with $m_l = 0$ hypothesis

$B^0 \rightarrow K^{*0} \mu\mu$ angular analysis

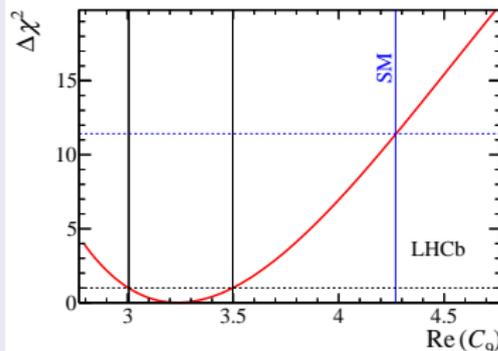
[JHEP 02 (2016) 104]

Optimized observables:

- $P'_{1,2,3}, P'_{4,5,6,8}$ – mostly independent from FF, normalized by fraction of longitudinal polarisation F_L , or by $\sqrt{F_L(1-F_L)}$



$$P'_5 = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$



$$\text{Re}(C_9^{\text{NP}}) = -1.04 \pm 0.25$$

Deviates by 3.4σ from SM

Conclusion

Conclusion

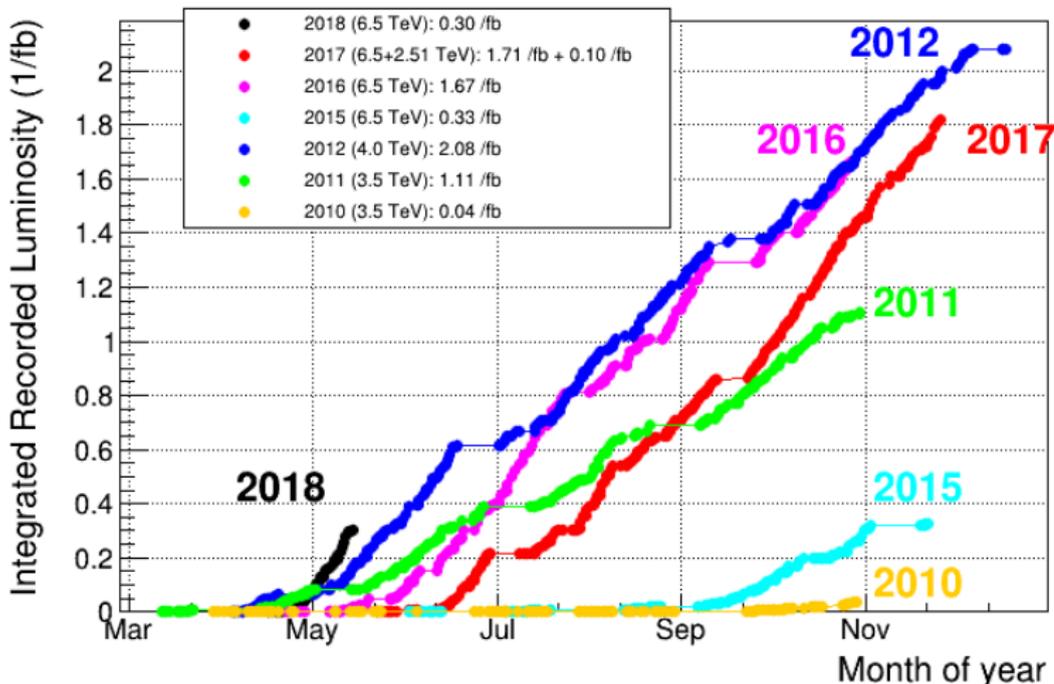
- LFU remains a hot topic
- Significant deviation from SM are observed in both $b \rightarrow cl\nu$ and $b \rightarrow sll$ transitions
 - $b \rightarrow cl\nu$: 4σ for $R(D)$ and $R(D^*)$ combined
 - $b \rightarrow cl\nu$: 2.1σ for $R(J/\psi)$
 - $b \rightarrow sll$: $2.1 - 2.4\sigma$ for $R(K)$, $R(K^*)$, 4σ combined
 - Values are consistent between different experiments
- Prospects:
 - Extension of searches to Run II
5.7fb⁻¹ of additional data at end of 2018
 - More H_c to test LFU:
 - Spin 0: D^0, D^+, D_s
 - Spin 1: $D^*, J/\psi$
 - Spin 1/2: Λ_c
 - Several of analyses are ongoing

Thanks for your attention!

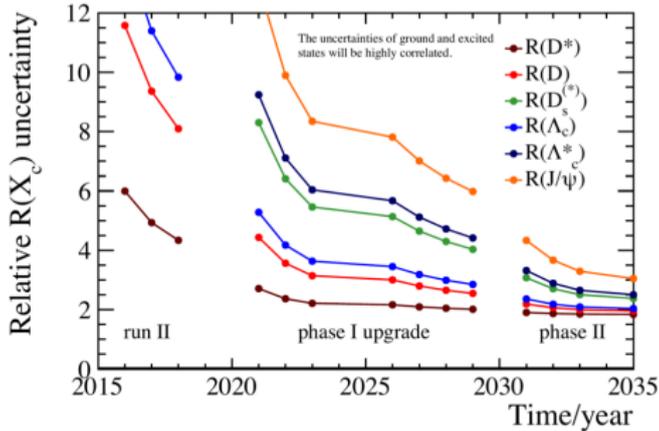
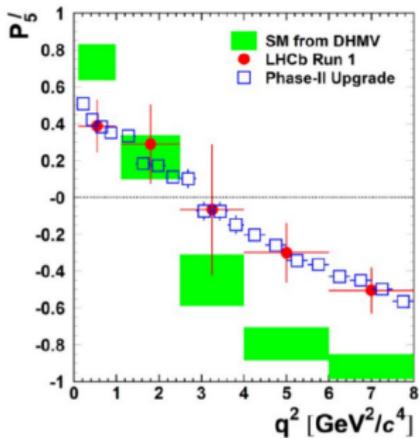
Back-up slides

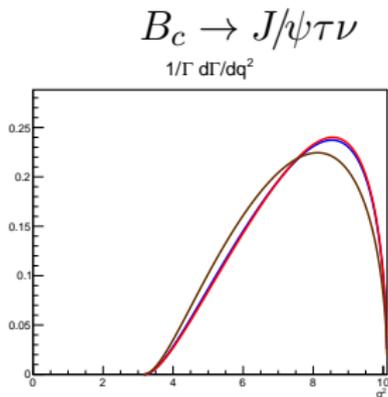
Integrated Luminosity

LHCb Integrated Recorded Luminosity in pp, 2010-2018

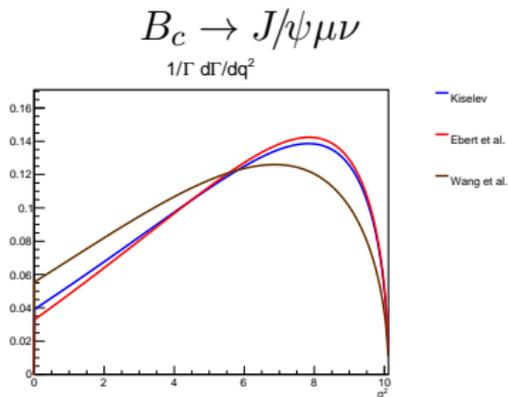


LHCb upgrade on LFU



$R(J/\psi)$ FF parametrisation

— Kiselev
— Ebert et al.
— Wang et al.



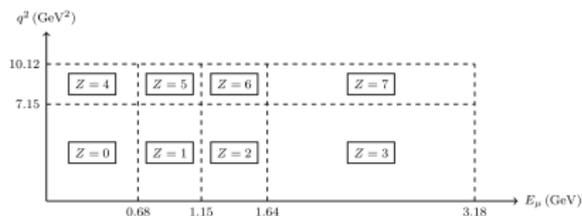
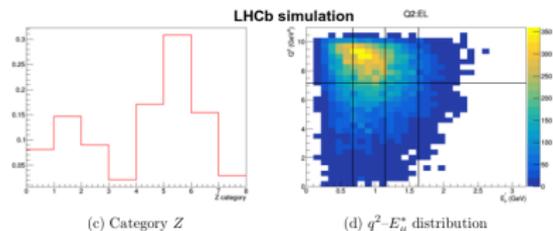
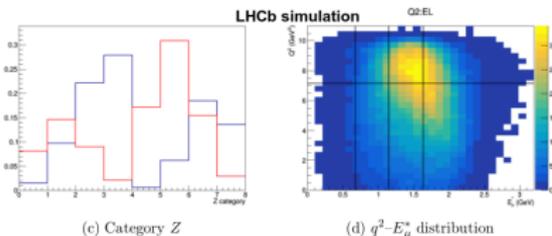
— Kiselev
— Ebert et al.
— Wang et al.

BCL¹ parametrisation: Expansion in z of order K

$$f(q^2) = \frac{1}{1 - q^2/M_{\text{pole}}^2} \sum_{k=0}^K a_k z(q^2)^k, \text{ where}$$

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_-}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_-}}$$

$$t_{\pm} = (m_{B_c} \pm m_{J/\psi})^2$$

$R(J/\psi)$ Z categorical variable● $B_c \rightarrow J/\psi \tau$ ● $B_c \rightarrow J/\psi \mu$ 

$R(J/\psi)$ with leptonic tau decay

[PRL 120 (2018) 121801]

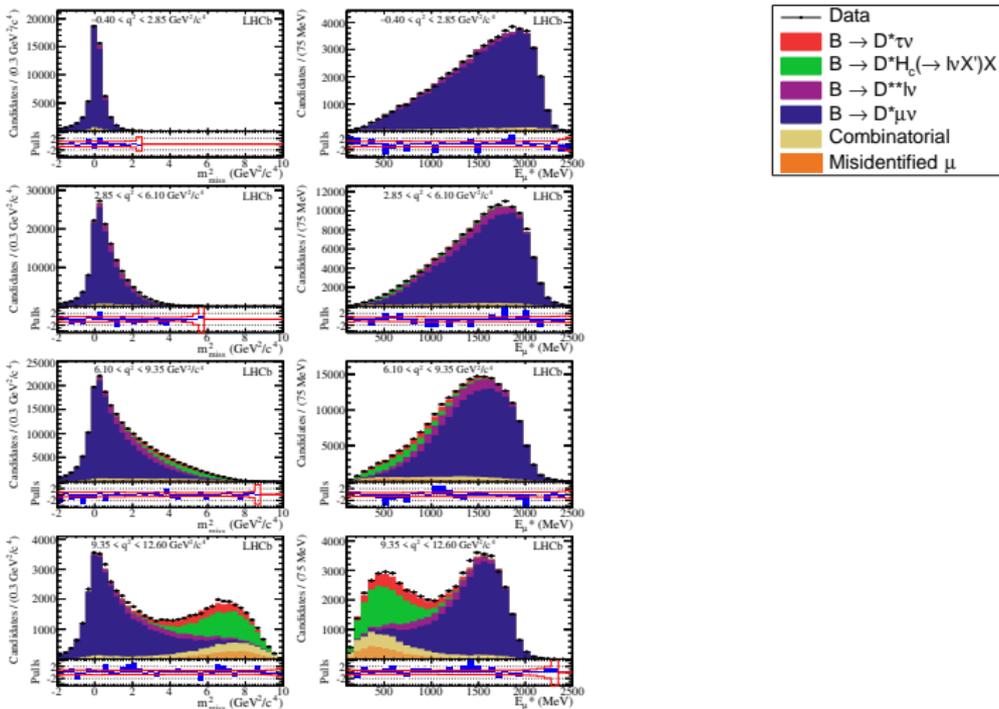
Systematic uncertainty

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

$R(D^*)$ with leptonic tau decay

Fit

[PRL 115 (2015) 111803]



$R(D^*)$ with leptonic tau decay

[PRL 115 (2015) 111803]

Systematic uncertainty

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

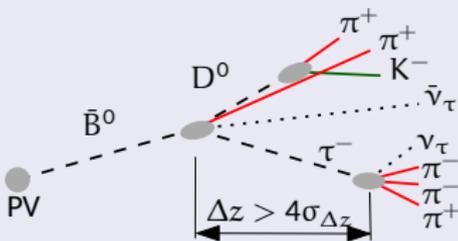
$R(D^*)$ with hadronic tau decay

Rejection of $B \rightarrow D^* 3\pi X$

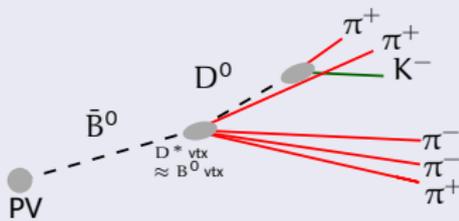
[PRD 97 (2018) 072013]

[PRL 120 (2018) 171802]

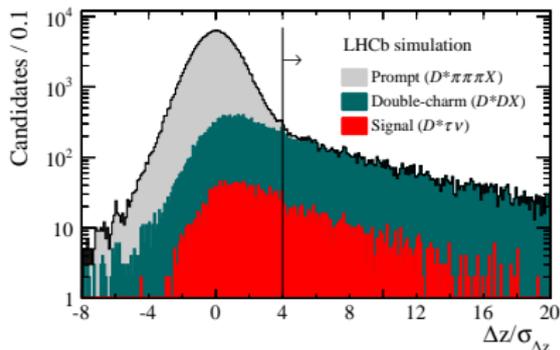
Signal:



Normalisation:



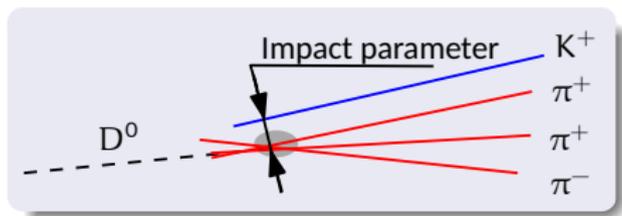
- Signal: detached τ vertex
- Vertex inversion cut:
 $\Delta z > 4\sigma_{\Delta z}$
 - S/B improves $\times 160$



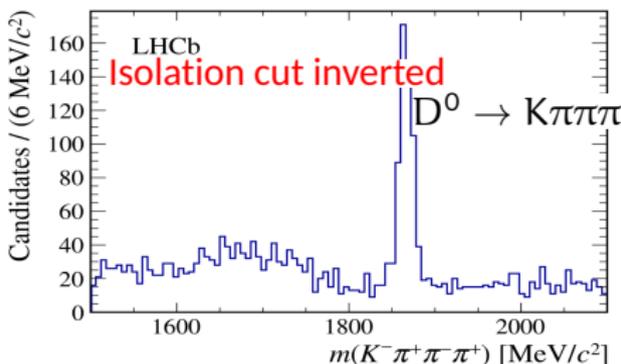
$R(D^*)$ with hadronic tau decayRejection of $B \rightarrow D^* D X$

[PRD 97 (2018) 072013]

[PRL 120 (2018) 171802]



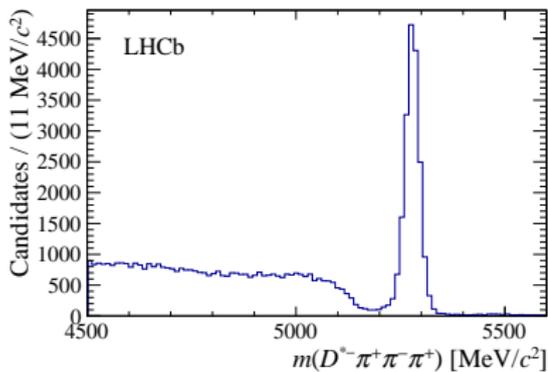
- Veto on additional particles
 - Charged isolation: cut on impact parameter
 - Neutral isolation: cut on calo energy



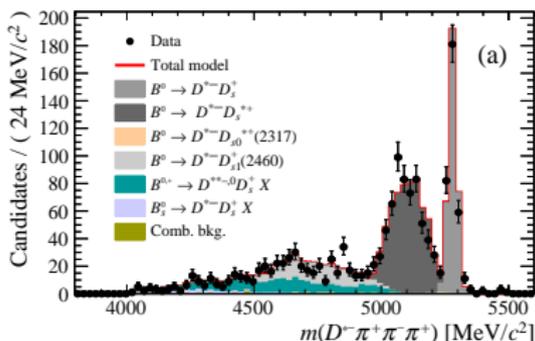
- Efficiency for signal: $\sim 80\%$
- Rejection of $B^0 \rightarrow D^{*-} D^0 K^+(X)$: $\sim 95\%$

$R(D^*)$ with hadronic tau decay

[PRD 97 (2018) 072013]

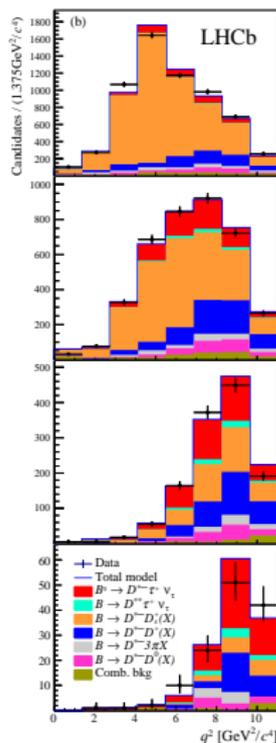
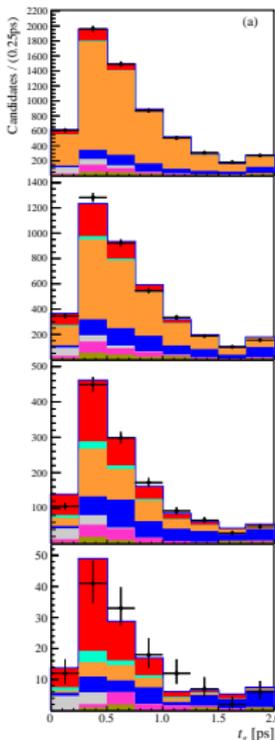
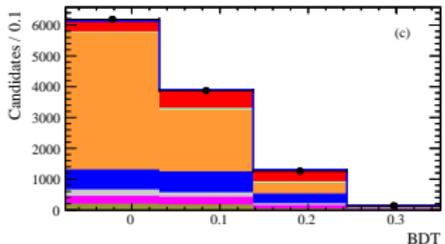
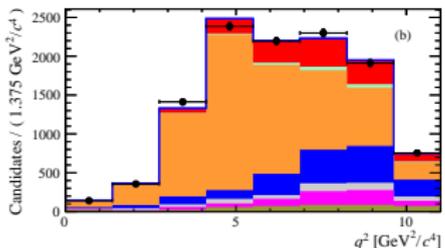
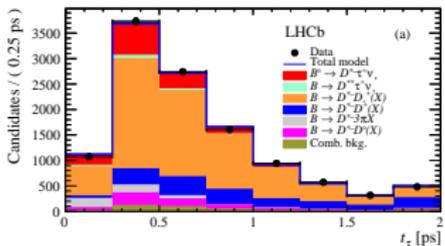
Control channel: $m(D^*3\pi)$ 

MC samples validation



$R(D^*)$ with hadronic tau decay

[PRD 97 (2018) 072013]



$R(D^*)$ with hadronic tau decay

Systematic uncertainty

[PRD 97 (2018) 072013]

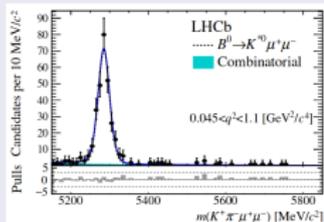
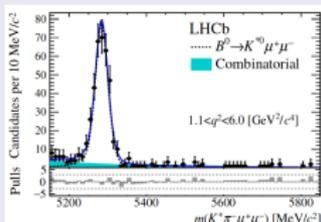
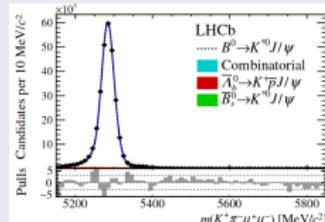
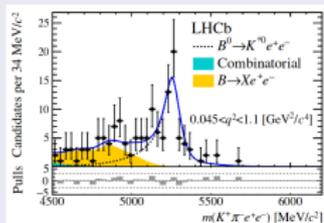
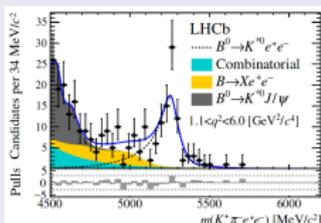
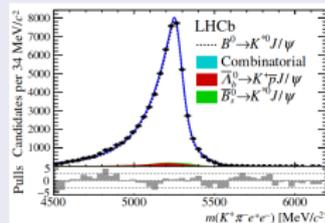
[PRL 120 (2018) 171802]

Contribution	Value in %
$\mathcal{B}(\tau^+ \rightarrow 3\pi\bar{\nu}_\tau)/\mathcal{B}(\tau^+ \rightarrow 3\pi(\pi^0)\bar{\nu}_\tau)$	0.7
Form factors (template shapes)	0.7
Form factors (efficiency)	1.0
τ polarization effects	0.4
Other τ decays	1.0
$B \rightarrow D^{**}\tau^+\nu_\tau$	2.3
$B_s^0 \rightarrow D_s^{**}\tau^+\nu_\tau$ feed-down	1.5
$D_s^+ \rightarrow 3\pi X$ decay model	2.5
D_s^+ , D^0 and D^+ template shape	2.9
$B \rightarrow D^* D_s^+(X)$ and $B \rightarrow D^* D^0(X)$ 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 $B^0 \rightarrow D^{*-} 3\pi$)	2.0
Total uncertainty	9.1

$b \rightarrow sll$ $R(K^*)$

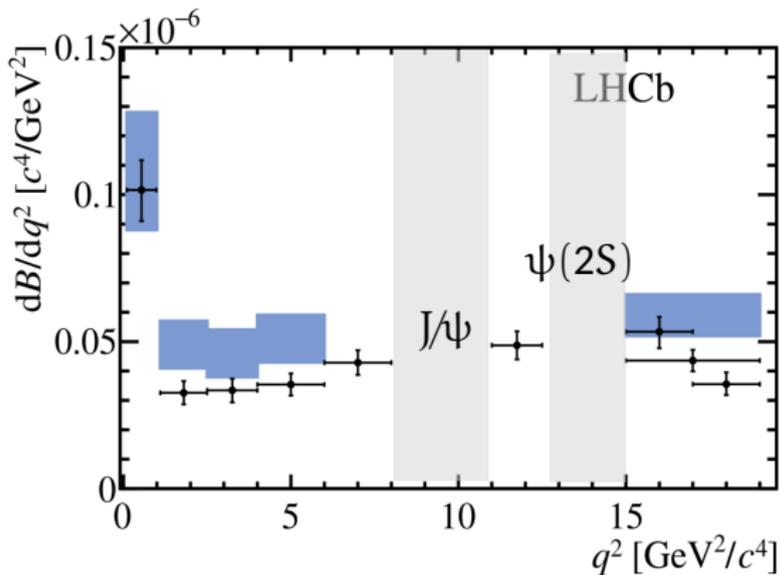
Fit

[JHEP 08 (2017) 055]

 $B \rightarrow K^{*0} \mu \mu$ Low q^2 : 285 ± 18 Central q^2 : 353 ± 21  J/ψ : 274416^{+602}_{-654} $B \rightarrow K^{*0} ee$ Low q^2 : 89 ± 11 Central q^2 : 111 ± 14  J/ψ : 58361^{+257}_{-256}

$B^0 \rightarrow K^* \mu\mu$ differential \mathcal{BR}

[JHEP 11 (2016) 047]



- Measured w.r.t. $B \rightarrow J/\psi K^*$
- Mild deviation in central q^2 region