Lepton Universality tests in semitauonic b-hadron decays at LHCb

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XUNTA DE GALICIA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

LHCb

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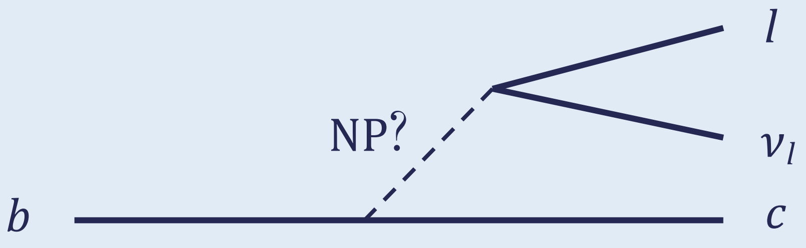
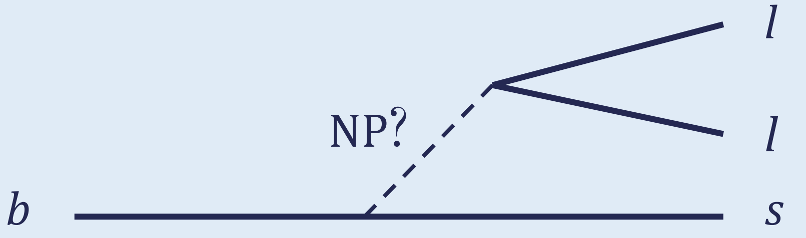
Lepton Flavor Universality

- In the SM, gauge bosons have universal coupling to leptons, independently of their family. This is called Lepton Flavor Universality (LFU).

e^-	μ^-	τ^-
ν_e	ν_μ	ν_τ
u	c	t
d	s	b

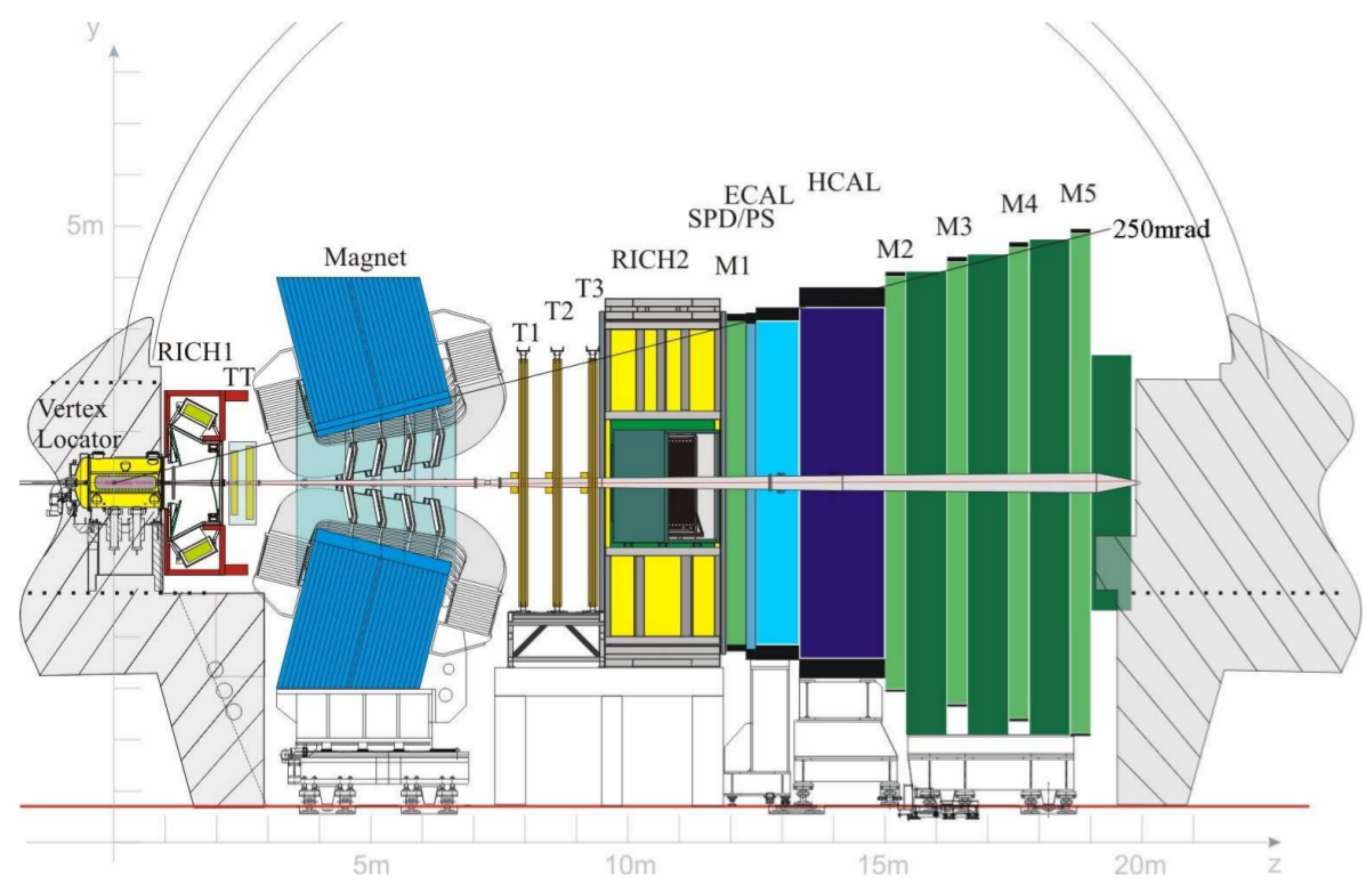


- Tensions between experiments and SM predictions found in:
  - Charged currents ($b \to cl\nu$)
  - Neutral currents ($b \to sll$)



- A violation of LFU would require the existence of new particles outside the SM (H^-, Z', W'^-, leptoquarks…).

LHCb detector



- High b-quark production:
  - Run1 (2011-2012, 7-8 TeV): $\sim 72\ \mu b$
  - Run2 (2015-2018, 13 TeV): $\sim 144\ \mu b$
- Excellent vertex and impact parameter resolution ($\sim 25\ \mu m$)
- b-hadrons highly boosted, giving large values of the impact parameter ($\sim 800\ \mu m$)
- Excellent PID performance for charged particles (muon efficiency of $\sim 97\%$)

[PRL 119 169901 (2017)]

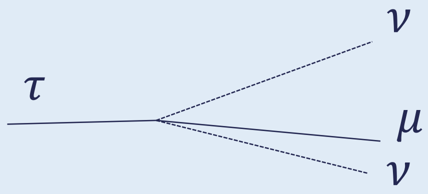
LFU tests at LHCb: charged currents

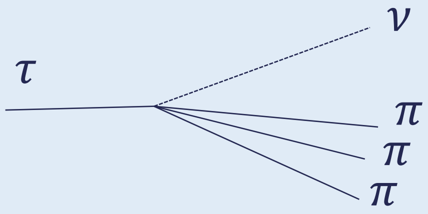
- $b{\to}cl\nu$ decays:

$$R(\mathcal{H}_c) \equiv \frac{\mathcal{B}(\mathcal{H}_b{\to}\mathcal{H}_c\tau\nu_\tau)}{\mathcal{B}(\mathcal{H}_b{\to}\mathcal{H}_c\mu\nu_\mu)} \,,$$

where

$$\mathcal{H}_b = B^0, B^+, B_s^0, \Lambda_b^0 \ldots$$
$$\mathcal{H}_c = D^{(*)0}, D^{(*)+}, D_s^+, \Lambda_c^+, J/\psi \ldots$$





  - In SM: tree-level decays mediated by a W boson.
  - Sensitivity to NP contributions at tree level.
  - Partial cancelation of form factor uncertainties.
  - High rate of charged current decays: $\mathcal{B}(B \to D^*\tau\nu_\tau) \approx 1.2\%$.

- Muonic channel: $\mathcal{B}(\tau^+ \to \mu^+\bar{\nu}_\mu\nu_\tau) \approx 17.39\%$
  - Systematic uncertainties cancel in the ratio $R(\mathcal{H}_c)$
  - Presence of inclusive $\mathcal{H}_b \to \mathcal{H}_c\mu\nu_\mu(\mathrm{X})$ decays
- Hadronic channel: $\mathcal{B}(\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\nu_\tau) \approx 13.51\%$
  - Only one neutrino
  - τ vertex reconstruction

[PRL 115 111803 (2015)]

$R(D^*)$ muonic

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

$$(p_B)_z = \frac{m_B}{m_{reco}}(p_{reco})_z$$

Both channels selected, and then disentangled using a multidimensional fit to:

- E_μ^* (B rest frame)
- $m_{miss}^2 = (p_B - p_{D^*} - p_\mu)^2$
- $q^2 = (p_B - p_{D^*})^2$

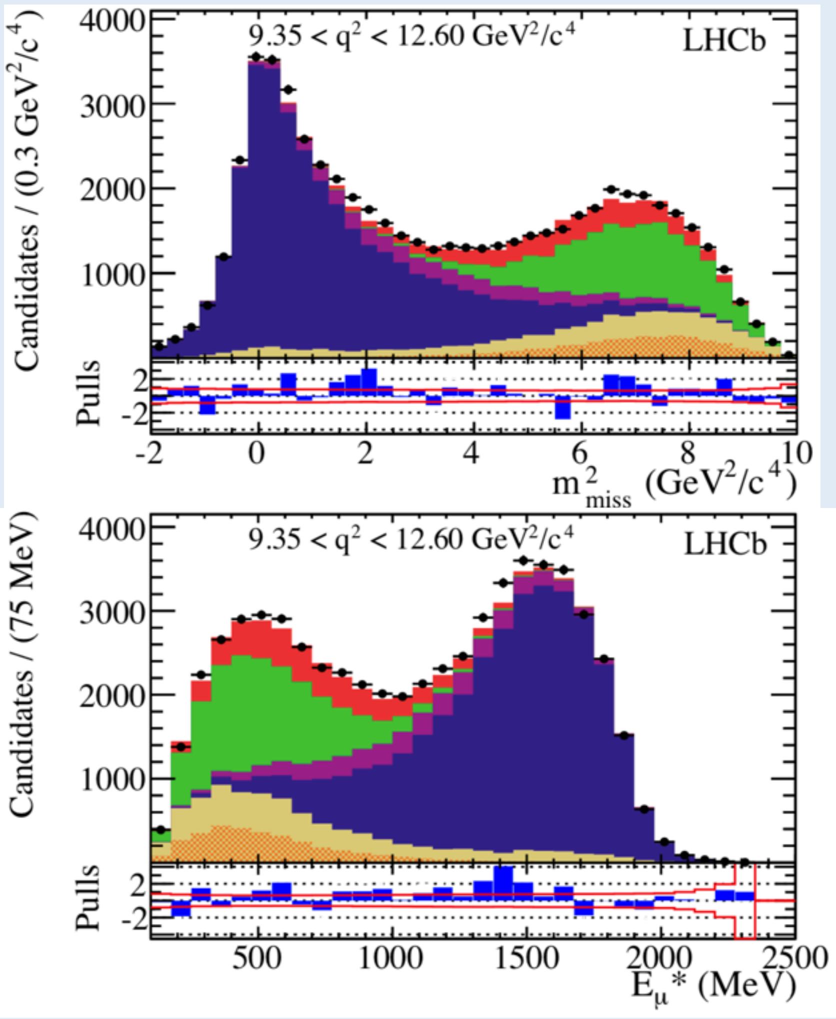
$$R(D^*)_{muonic} = \frac{N(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{N(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)} \frac{1}{\mathcal{B}(\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau)} \frac{\epsilon_{norm}}{\epsilon_{sig}}$$

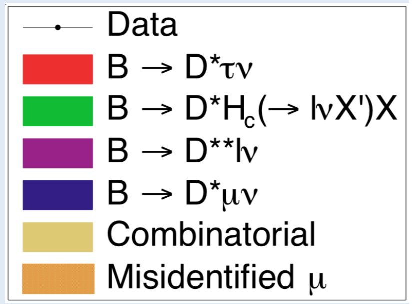
$$R(D^*)_{muonic} = 0.336 \pm 0.027 \pm 0.030$$

2.1σ above SM prediction

$R(D^*)_{SM} = 0.252 \pm 0.003$

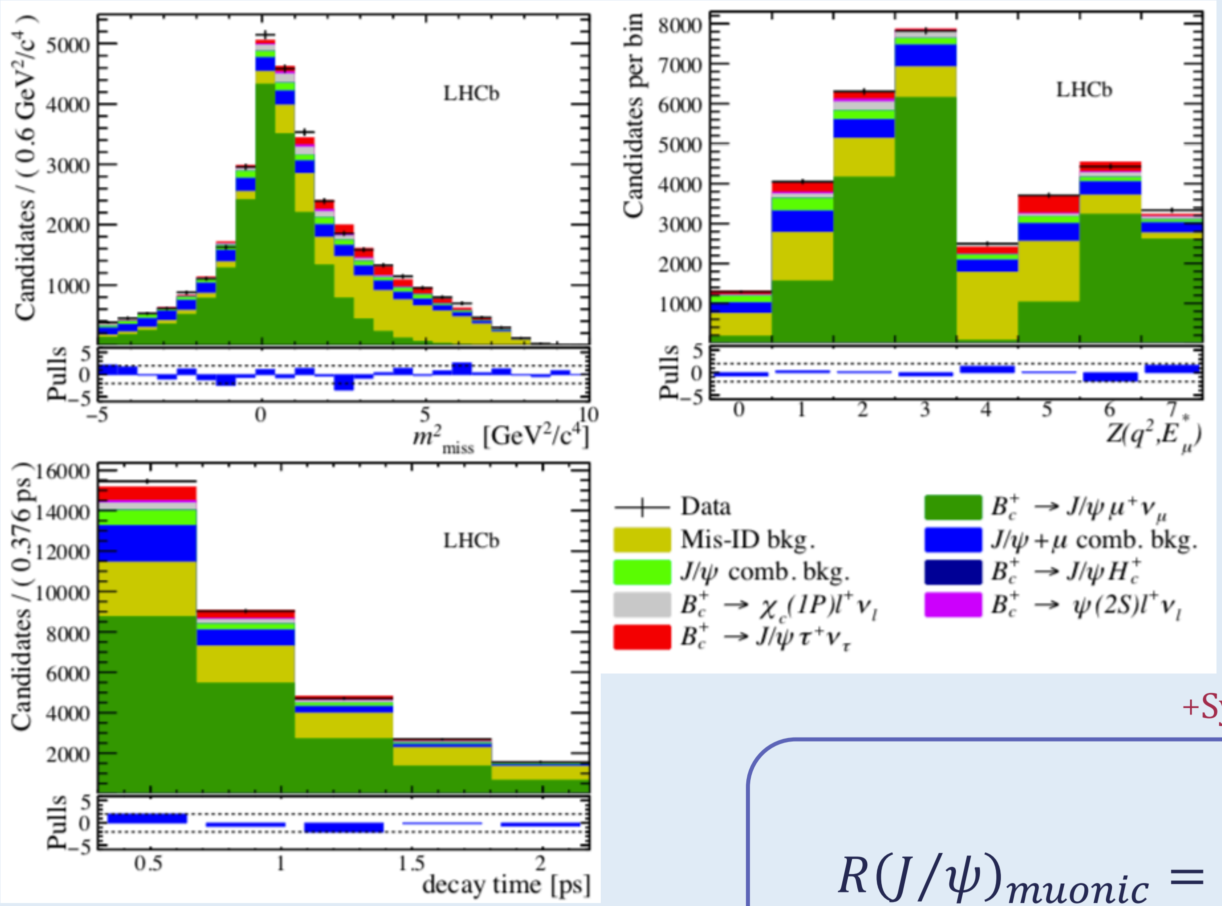
(Run1)





[PRL 120 121801 (2018)]

$R(J/\psi)$ muonic



(Run1)

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

Similar to R(D*) analysis, fit using:

- $m^2_{miss} = (p_B - p_{J/\psi} - p_\mu)^2$
- $q^2 = (p_B - p_{J/\psi})^2$
- E^*_μ (B rest frame)
- B_c decay time

(q^2 and E^*_μ combined into $Z(q^2, E^*_\mu)$)

$$R(J/\psi)^{(raw)}_{muonic} = \frac{N(B_c^+ \to J/\psi\,\tau^+\nu_\tau)}{N(B_c^+ \to J/\psi\,\mu^+\nu_\mu)} \frac{1}{\mathcal{B}(\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau)} \frac{\epsilon_{norm}}{\epsilon_{sig}}$$

+Systematic bias in the fit

$$R(J/\psi)_{muonic} = 0.71 \pm 0.17 \pm 0.18$$

2σ above SM prediction
$R(J/\psi)_{SM} \in [0.25, 0.28]$

$R(D^*)$ hadronic

[PRD 97 072013 (2018)]
[PRL 120 171802 (2018)]

$$\mathcal{K}(D^{*-}) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)} = \frac{N_{sig}}{N_{norm}} \frac{\epsilon_{norm}}{\epsilon_{sig}} \frac{1}{\mathcal{B}(\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau) + \mathcal{B}(\tau^+ \to \pi^+\pi^-\pi^+\pi^0\bar{\nu}_\tau)}$$

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

(external inputs)

$\mathcal{B}(\tau^+ \to 3\pi\bar{\nu}_\tau) + \mathcal{B}(\tau^+ \to 3\pi\pi^0\bar{\nu}_\tau) = (13.81 \pm 0.07)\%$

$\mathcal{B}(B^0 \to D^{*-}3\pi) = (7.21 \pm 0.28)\times 10^{-3}$

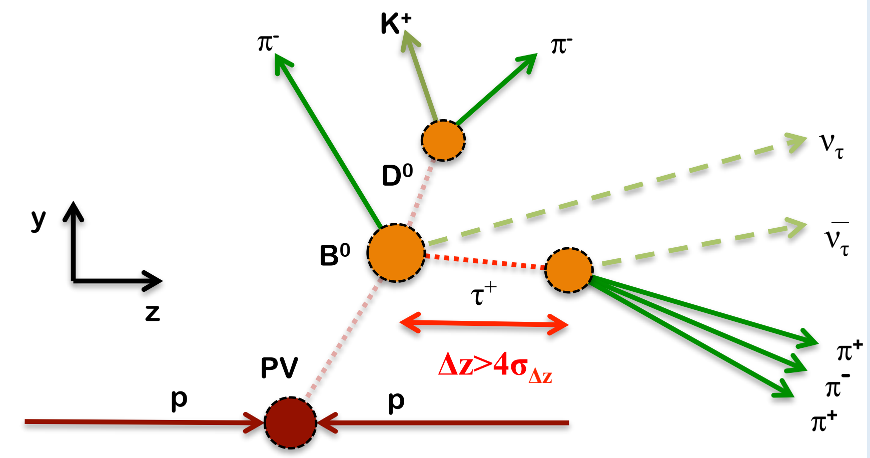
$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu) = (4.88 \pm 0.10)\times 10^{-2}$

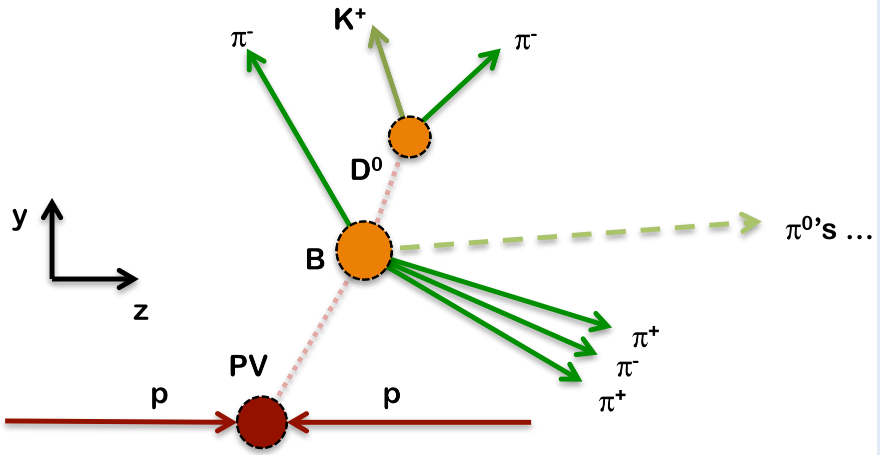
The presence of only one neutrino allows the τ and B^0 momenta to be determined up to a two-fold ambiguity.

N_{sig} obtained from a binned fit in these variables:

- Squared transferred momentum, q^2
- τ decay time, t_τ
- Output of a BDT, which takes as input 18 variables (kinematic variables of the decay chain and neutral isolation properties)

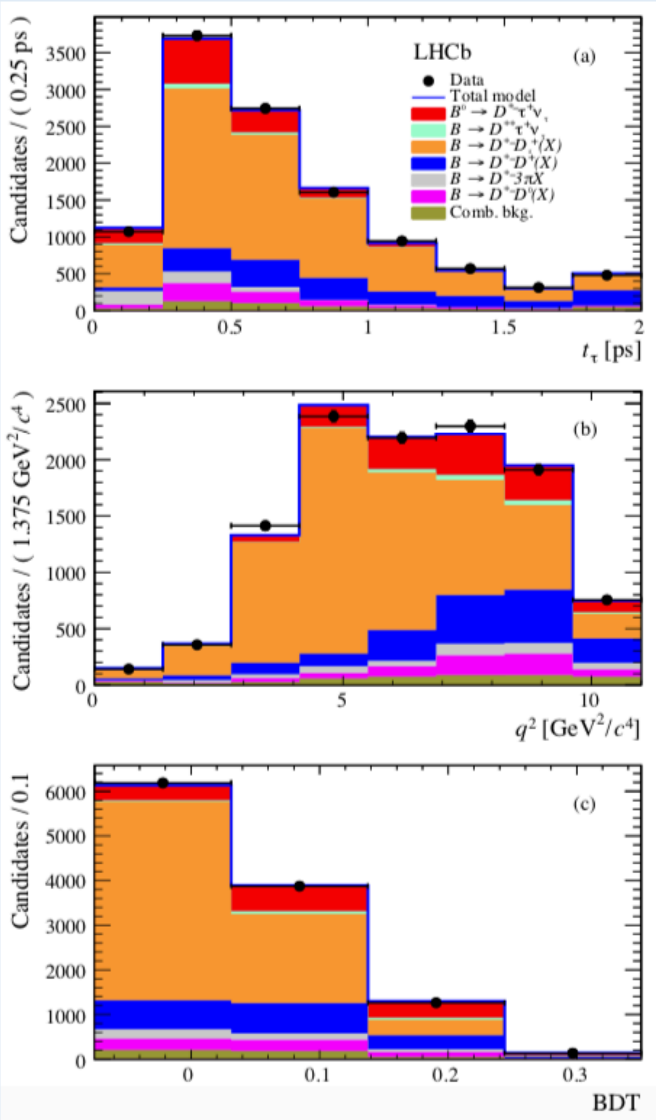
N_{norm} obtained by fitting the invariant mass distribution of the $D^{*-}3\pi$ system around the B^0 mass.

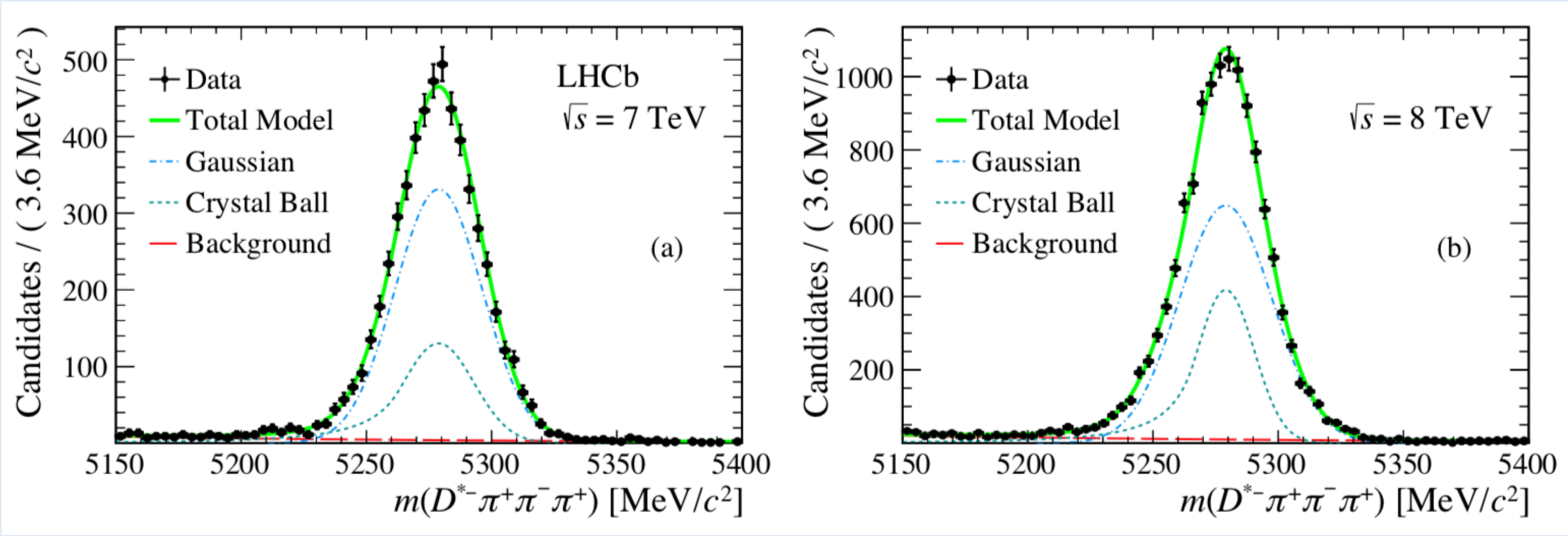




$R(D^*)$ hadronic

[PRD 97 072013 (2018)]
[PRL 120 171802 (2018)]





(Run1)

$N_{norm} = 17808 \pm 143$

$N_{sig} = 1296 \pm 86$ → $\mathcal{K}(D^{*-}) = 1.97 \pm 0.13(\text{stat}) \pm 0.18(\text{syst})$

$R(D^{*-})_{had} = 0.291 \pm 0.019 \pm 0.029$

1.1σ higher than SM prediction
$R(D^*)_{SM} = 0.252 \pm 0.003$

Combined measurement of $R(D)$ and $R(D^*)$

(Ongoing analysis with Run2 data)

We aim to measure $R(D)$ and $R(D^*)$ via three-prong tau decays, using the data:

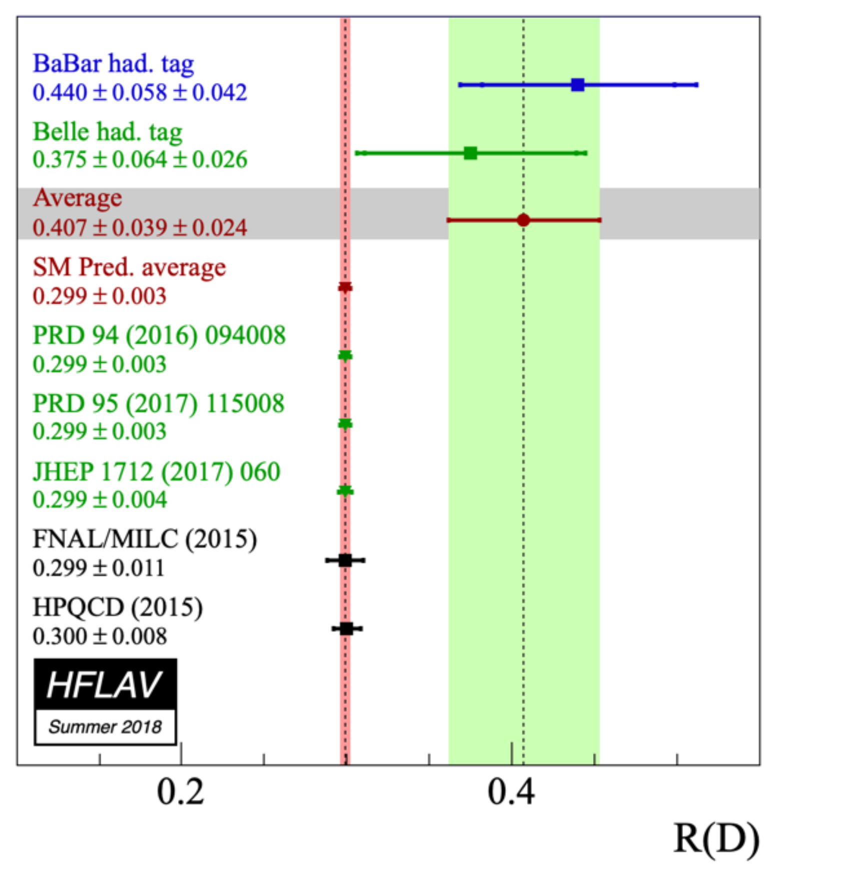
- $D^0 3\pi$ with $D^0 \to K\pi$

  This data sample includes contributions from $B^- \to D^0 \tau\nu$, $B^0 \to D^*(\to D^0\pi)\tau\nu$, $B^- \to D^{*0}(\to D^0\pi^0, \gamma)\tau\nu$ …

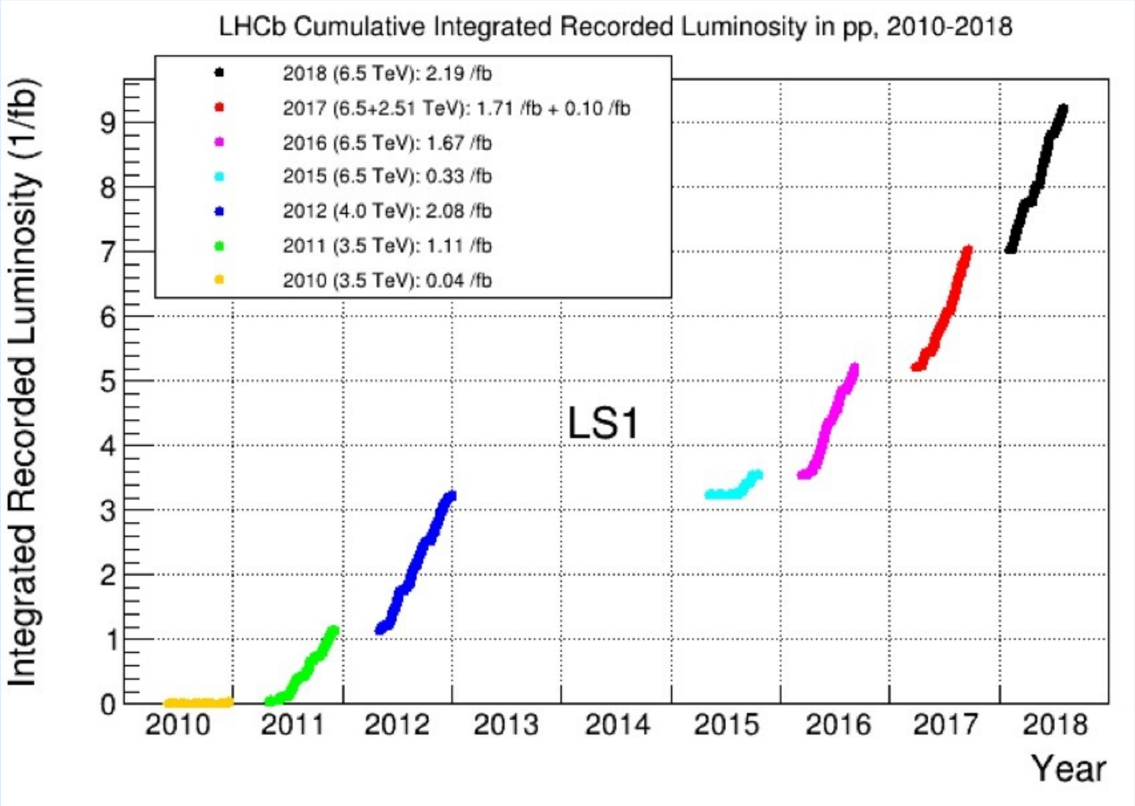
- $D^{\pm} 3\pi$ with $D^{\pm} \to K\pi\pi$

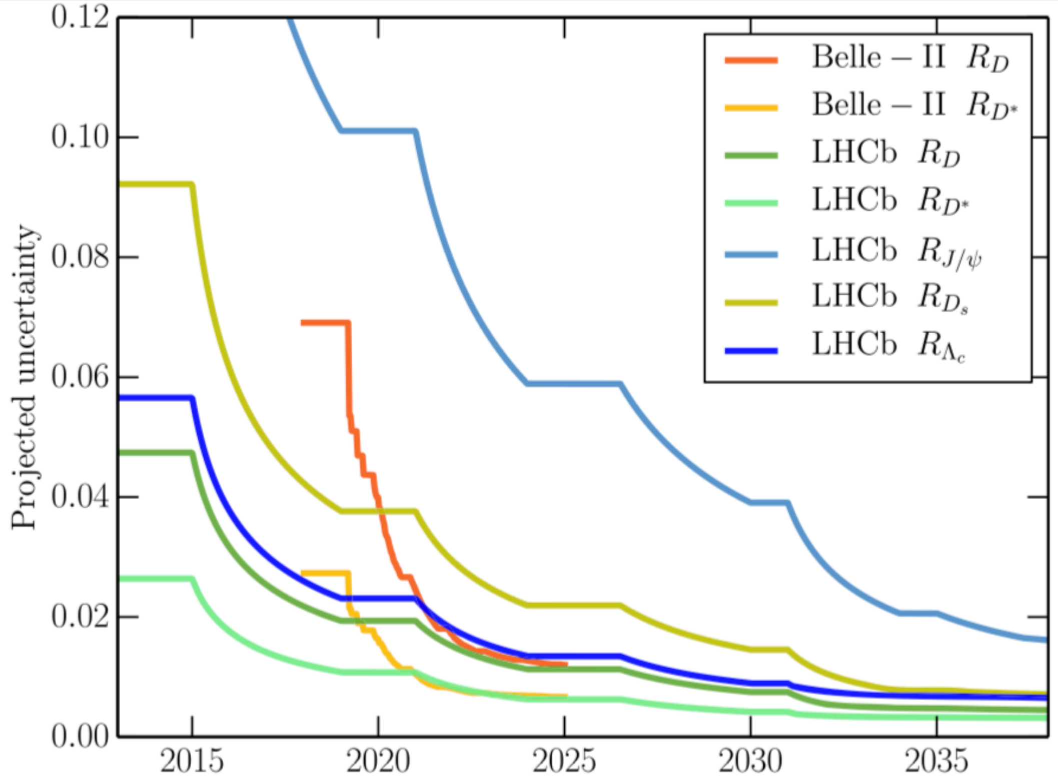
  This data sample includes contributions from $B^- \to D^- \tau\nu$, $B^0 \to D^*(\to D^-\pi^0)\tau\nu$ …

The analysis of these samples will provide two independent measurements of $R(D)$ and $R(D^*)$.



Uncertainty projections





Integrated luminosity:
Run1: ~ 3.2 fb^{-1}
Run1+Run2: ~ 9.2 fb^{-1}

→

$b\bar{b}$ pairs produced:
Run1: ~ 2.5×10^{11}
Run1+Run2: ~ 11×10^{11}

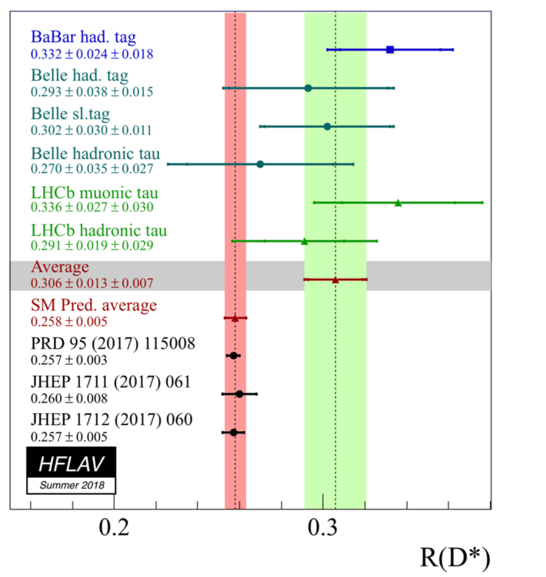
→

~52% statistical uncertainty reduction
Run1: $\sigma^{stat}_{R(D^*)} = 0.019$
Run1+Run2: $\sigma^{stat}_{R(D^*)} \approx 0.0091$

[HFLAV R(D) and R(D*) averages]
[Moriond Talk by G.Caria (2019)]

Conclusions and prospects

2.3σ difference in $R(D)$, 3.0σ in $R(D^*)$, 3.78σ combined.
New Belle preliminary average compatible within 2σ,
decreasing the global average to $\mathbf{3.1\sigma}$ away from SM.

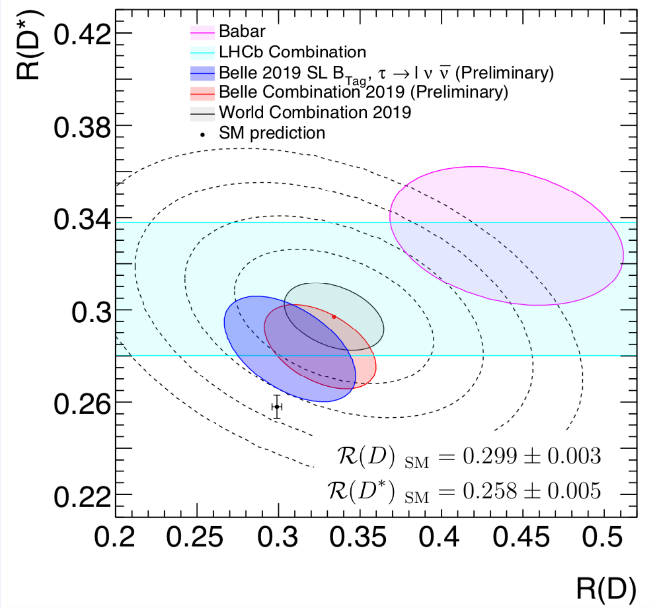


Potential for NP? we need smaller uncertainties!

With Run2 data:

- Updated measurements with reduced uncertainties
- Hadronic $R(J/\psi)$
- Muonic and hadronic measurements of $R(D^+), R(D^0), R(D_s^+), R(\Lambda_c)$

Stay tuned!

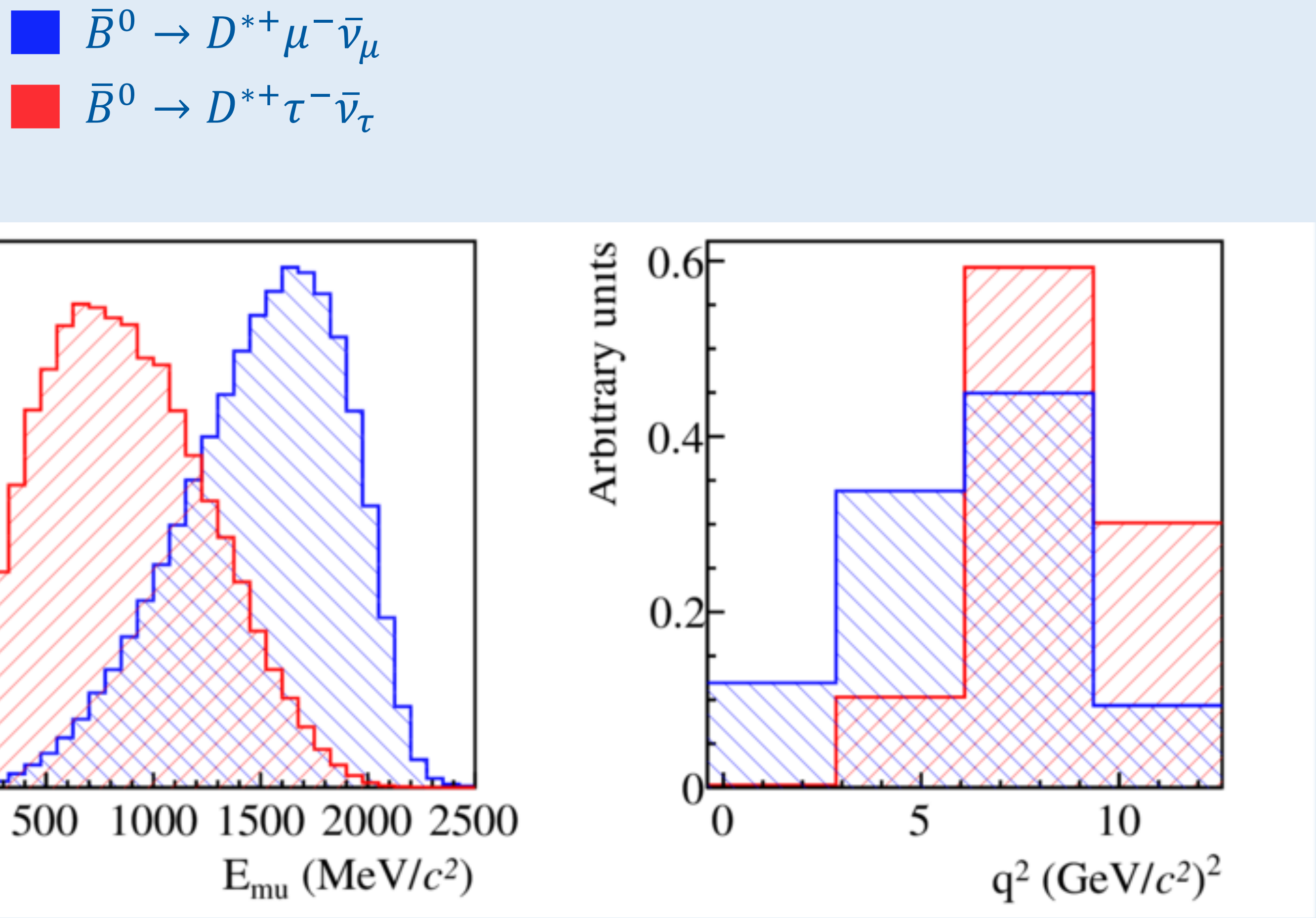


Backup Slides

$R(D^*)$ muonic: systematic uncertainties

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

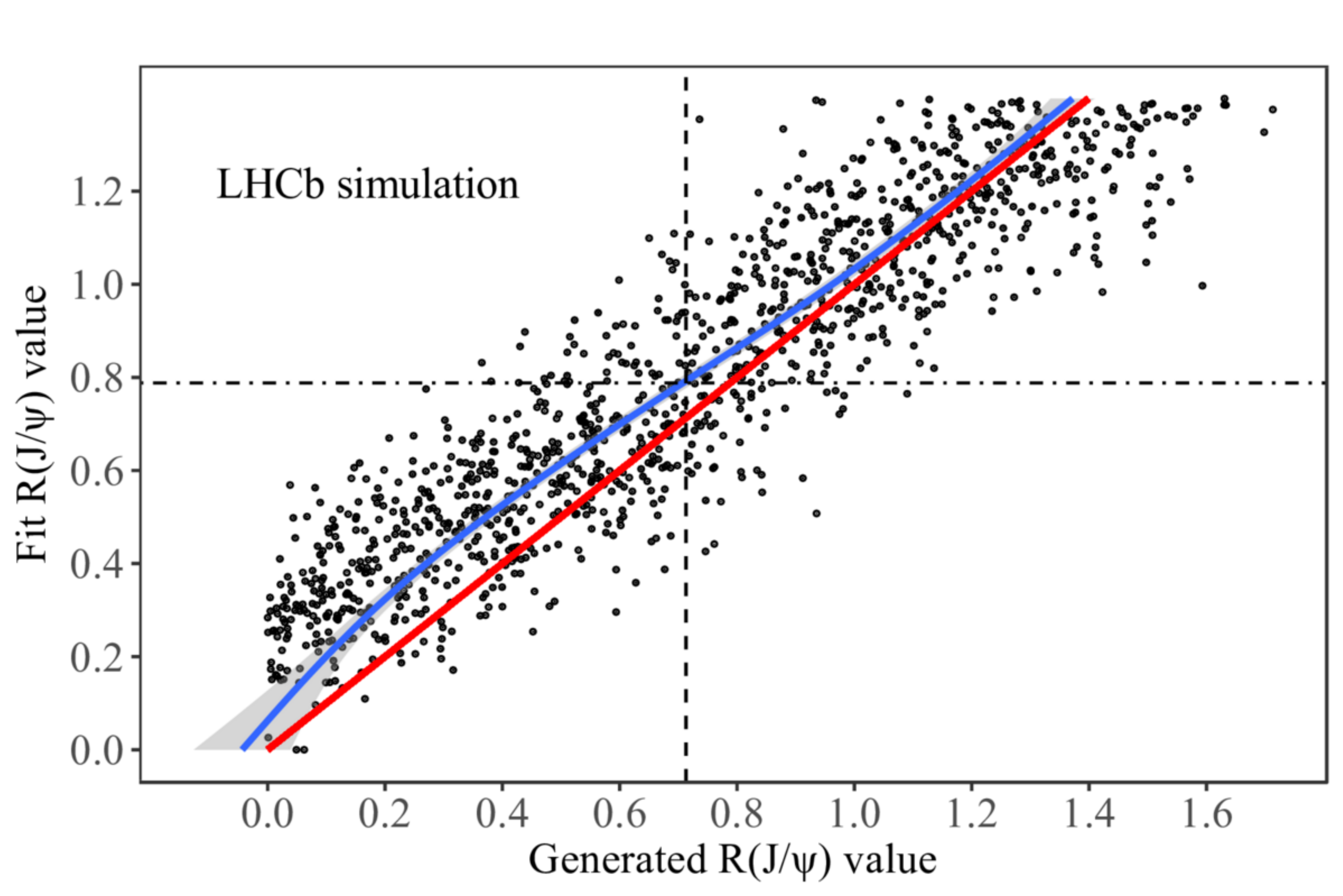
$R(D^*)$ muonic: signal discrimination



$R(J/\psi)$ muonic: systematic uncertainties

Source of uncertainty	**Size ($\times 10^{-2}$)**
Limited size of simulation samples	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
Misidentification background strategy	5.6
Combinatorial background cocktail	4.5
Combinatorial J/ψ sideband scaling	0.9
$B_c^+ \to J/\psi H_c X$ contribution	3.6
Semitauonic $\psi(2S)$ and χ_c feed-down	0.9
Weighting of simulation samples	1.6
Efficiency ratio	0.6
$\mathcal{B}(\tau^+ \to \mu^+ \nu_\mu \overline{\nu}_\tau)$	0.2
Total systematic uncertainty	**17.7**
Statistical uncertainty	**17.3**

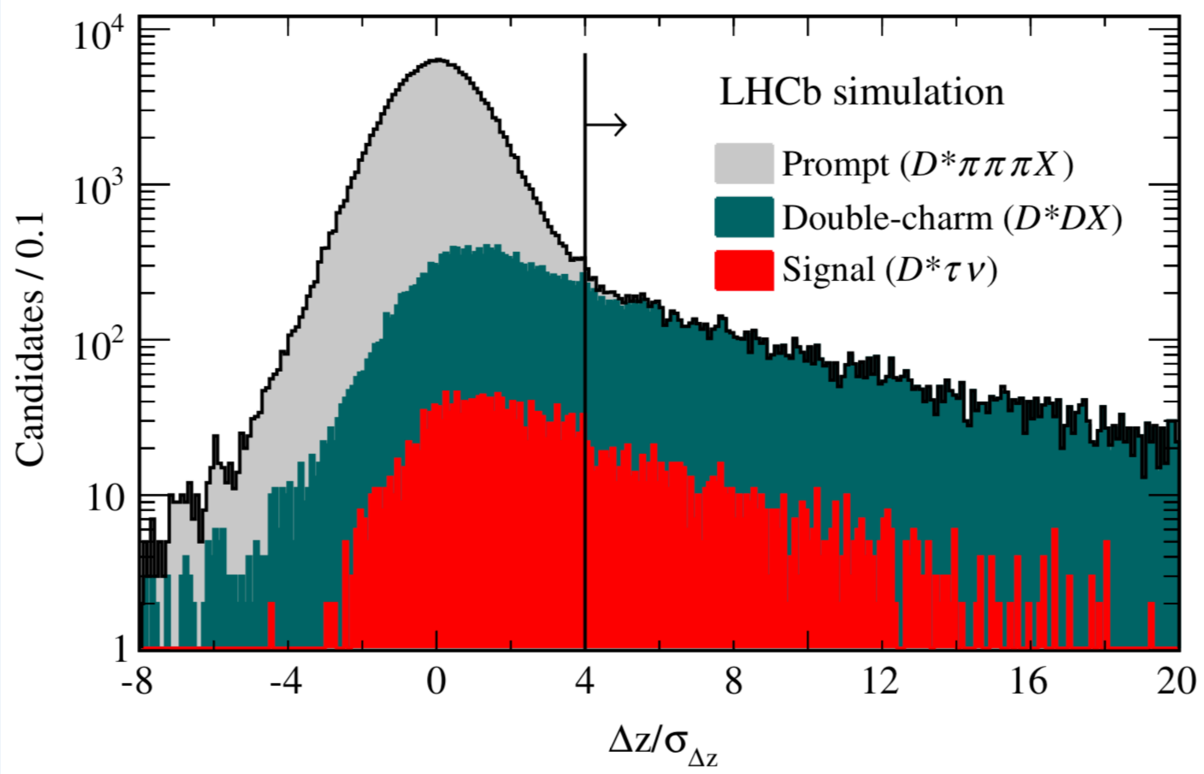
$R(J/\psi)$ muonic: systematic uncertainties

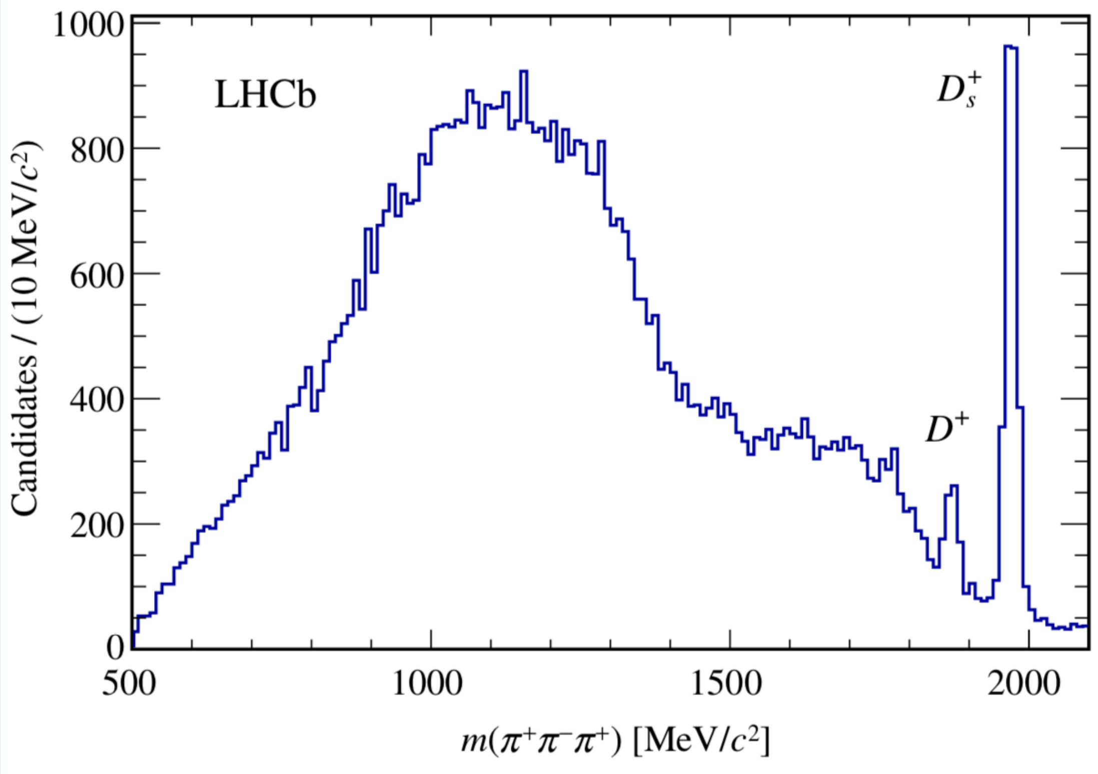


$R(D^*)$ hadronic: systematic uncertainties

Source	$\delta R(D^{*-})/R(D^{*-})[\%]$
Simulated sample size	4.7
Empty bins in templates	1.3
Signal decay model	1.8
$D^{**}\tau\nu$ and $D_s^{**}\tau\nu$ feeddowns	2.7
$D_s^+ \to 3\pi X$ decay model	2.5
$B \to D^{*-}D_s^+X$, $B \to D^{*-}D^+X$, $B \to D^{*-}D^0X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-}3\pi X$ background	2.8
Efficiency ratio	3.9
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0
Total uncertainty	9.1

$R(D^*)$ hadronic: detached vertex cut





Prompt background reduced by three orders of magnitude
40% of signal retained

$R(D^*)$ hadronic: BDT