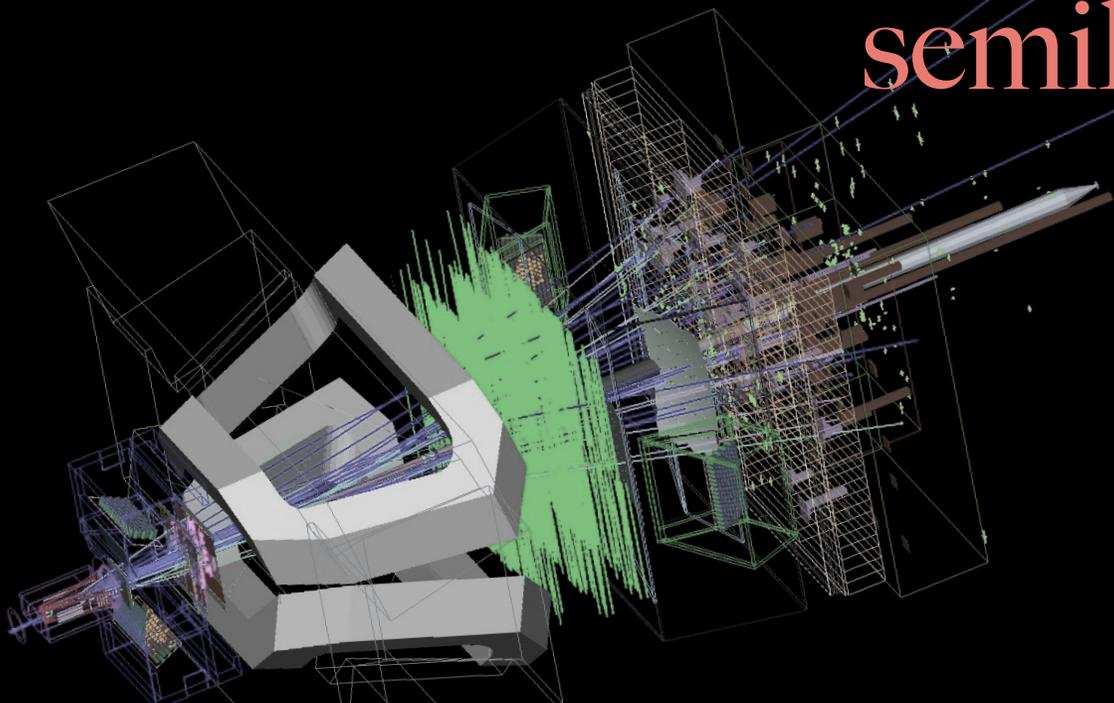




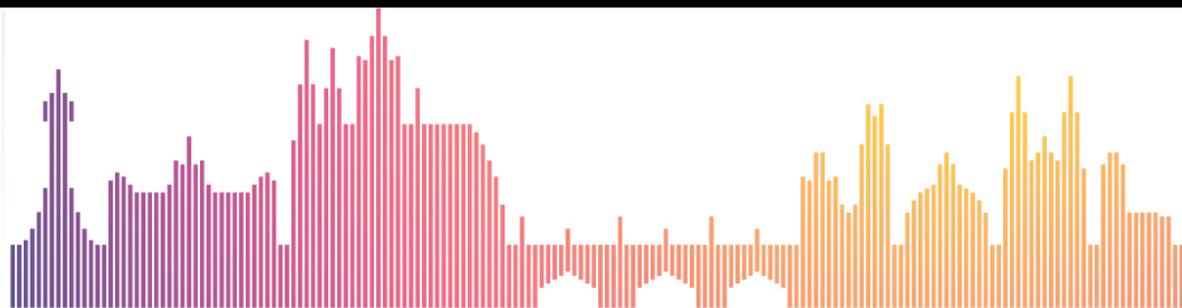
Lepton Universality tests using semileptonic b-hadron decays



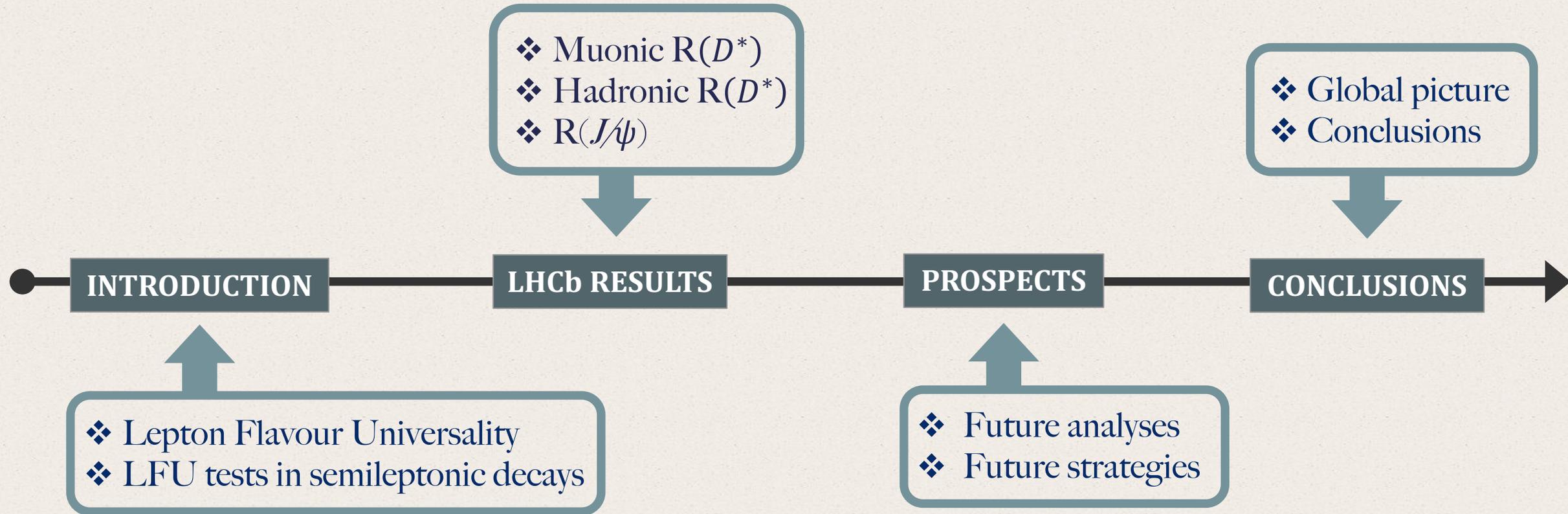
Beatriz García Plana
On behalf of the LHCb Collaboration
Universidade de Santiago de Compostela

ICHEP 2020 | PRAGUE

40th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS
30 JULY - 5 AUGUST PRAGUE, CZECH REPUBLIC

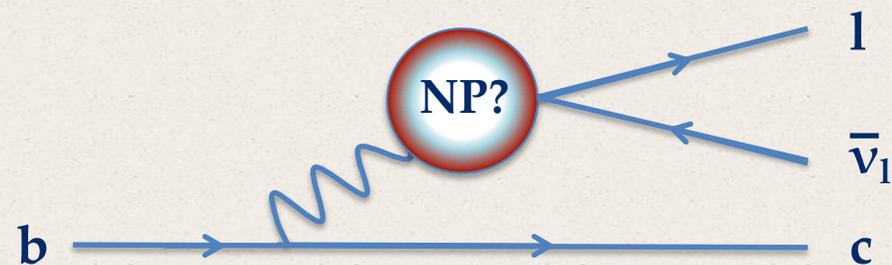


Today's outline



Lepton Flavour Universality

- SM predicts **Lepton Flavour Universality (LFU)**: equal couplings between gauge bosons and the three lepton families
- Observation of violation of LFU would be sign of **new physics (NP)**
- A large class of BSM models contain new interactions that involve third generations of quarks and leptons:
 - Charged Higgs
 - Leptoquarks
 - Z'
 - W'
 - ...
- Tensions between SM expectation and experimental results:
 - Charged currents: $b \rightarrow c l \nu$ *In this talk* 😊
 - Neutral currents: $b \rightarrow s l l$ *See talk 31st July* ➔



Lepton Flavour Universality tests in electroweak penguin decays at LHCb
virtual conference

Carla Marin Benito
09:43 - 09:58

LFU tests in semileptonic decays

Tree level decays in the SM, mediated by a W boson

$$R(\mathcal{H}_c) = \frac{\mathcal{B}(\mathcal{H}_b \rightarrow \mathcal{H}_c \tau \nu_\tau)}{\mathcal{B}(\mathcal{H}_b \rightarrow \mathcal{H}_c \mu \nu_\mu)}$$

with

$$\mathcal{H}_c = D^{*+}, D^{*0}, D^0, D^+, D_s, \Lambda_c^{(*)}, J/\psi \dots$$

$$\mathcal{H}_b = B^0, B_{(c)}^+, \Lambda_b^0, B_s^0 \dots$$

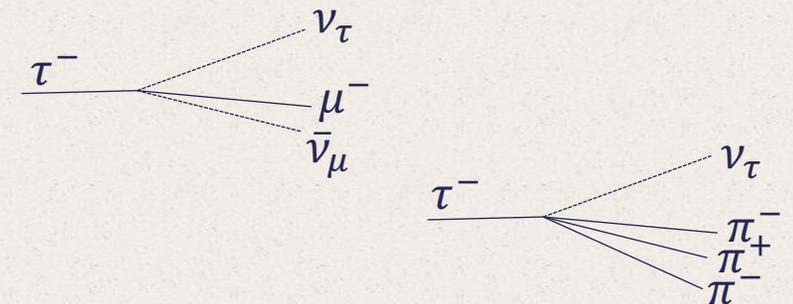
○ **Clean prediction from SM**

- Partial cancellation of hadronic form factor uncertainties in the ratio
- **High rate** of charged current decays: $\mathcal{B}(B \rightarrow D^* \tau \nu) \sim 1.2\%$ in SM
- Deviation from unity due to different lepton masses (τ, μ)



At LHCb...

- Missing momentum of neutrinos: Missing kinematic constraints
- B momentum unknown: needed approximations to reconstruct it
- **Two reconstruction channels for τ**
 - **Muonic mode:** $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$
 - **Hadronic mode:** $\tau^- \rightarrow \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$



R(D*) muonic at LHCb

First measurement of R(D*) in a hadron collider, using the muonic decay of $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$

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

Features of the analysis:

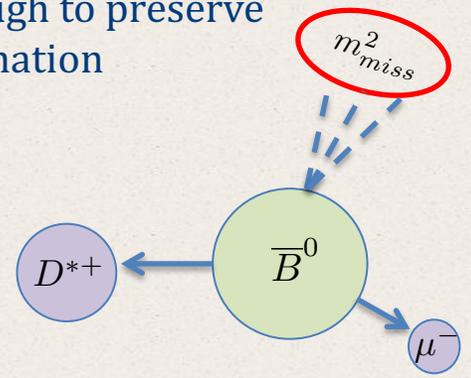
- Missing kinematic constraints: Rest frame approximation

$$(\gamma\beta_z)_B = (\gamma\beta)_{D^*\mu} \Rightarrow (p_z)_B = \frac{m_B}{m(D^*\mu)} (p_z)_{D^*\mu}$$

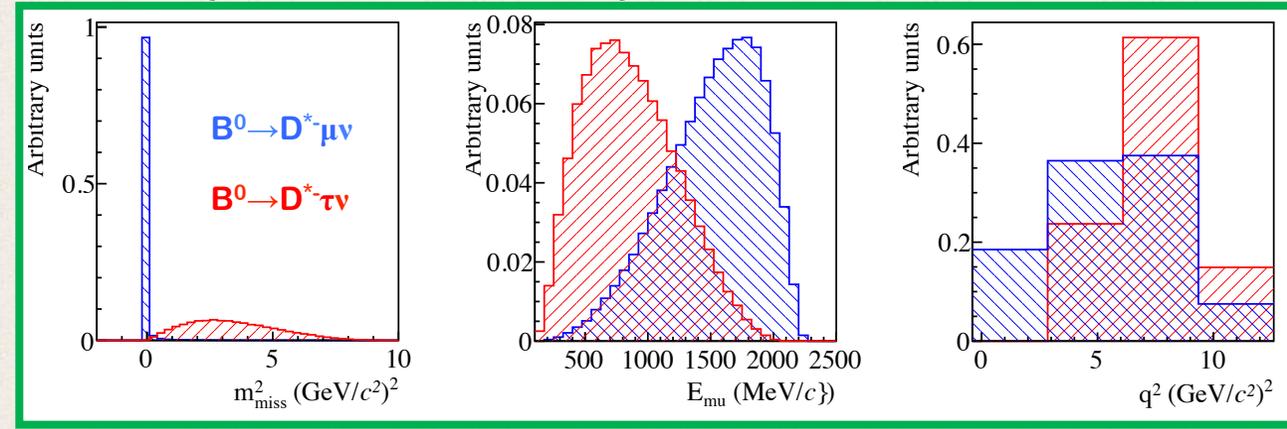
- 18 % resolution on p_B , good enough to preserve signal and normalization discrimination

Variables:

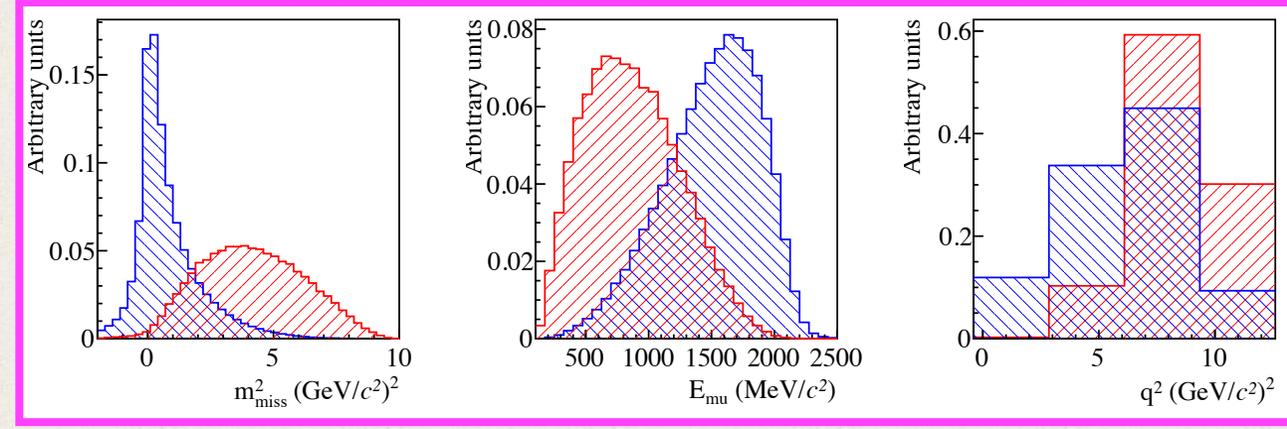
- E_μ (B rest frame)
- $m_{miss}^2 = (p_B - p_{D^*} - p_\mu)^2$
- $q^2 = (p_B - p_{D^*})^2$



MC truth (before detector effects)



MC reconstructed (including detector effects)



R(D*) muonic at LHCb

[PRD 115, 111803 (2015)]



Result: separate τ and μ components via a 3D binned template fit to:

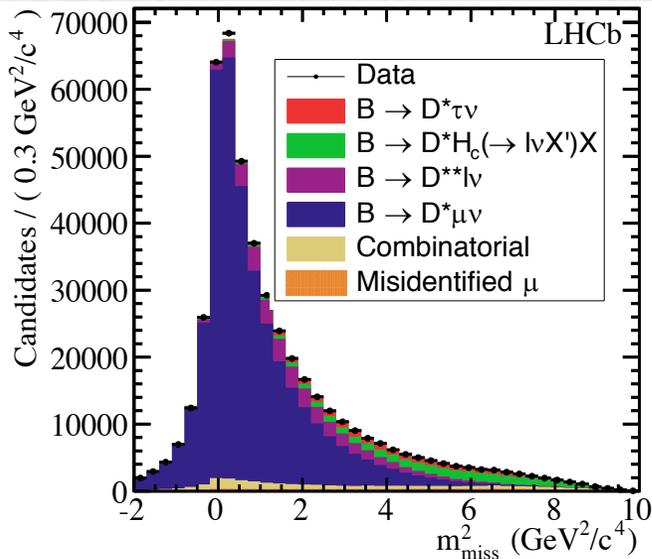
- E_μ (B rest frame)
- $m_{miss}^2 = (p_B - p_{D^*} - p_\mu)^2$
- $q^2 = (p_B - p_{D^*})^2$

$$R(D^*) = 0.336 \pm 0.027(stat) \pm 0.030(syst)$$

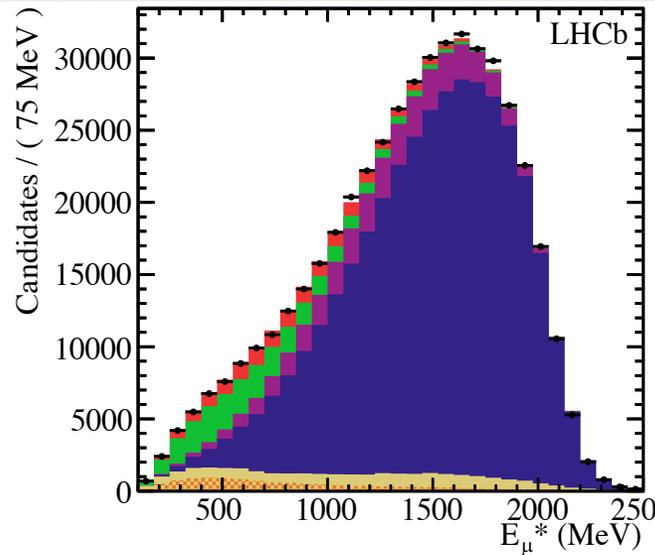
~2.1 σ from SM

[HFLAV 2019]

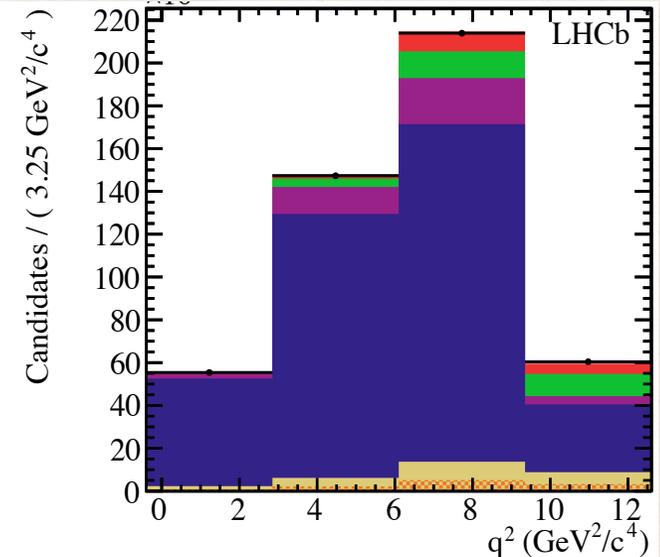
m^2_{miss}



E_μ^*



q^2



[Run 1 data]

R(D^*) hadronic at LHCb

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



First measurement of R(D^*) using the hadronic τ decay with $\tau^+ \rightarrow \pi^+ \pi^- \pi^+ (\pi^0) \nu_\tau$

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

Overlapping signal
decay mode

- Approximations are done to reconstruct the B and τ momentum
- Signal and normalization same visible state: $D^{*-} \pi^+ \pi^- \pi^+$
- Most of the theoretical and experimental uncertainties are cancelled out in the ratio
- $R(D^*)$ obtained from:

τ decay mode	BR (%) [PDG-2017]
$\tau \rightarrow \mu \nu_\mu \nu_\tau$	17.39 ± 0.04
$\tau \rightarrow e \nu_e \nu_\tau$	17.82 ± 0.04
$\tau \rightarrow \pi^+ \pi^- \pi^+ \nu_\tau$	9.31 ± 0.05
$\tau \rightarrow \pi^+ \pi^- \pi^+ \pi^0 \nu_\tau$	4.62 ± 0.05
$\tau \rightarrow \pi \nu_\tau$	10.82 ± 0.05
$\tau \rightarrow \rho \nu_\tau$	25.49 ± 0.09

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

[4.0 % precision]

[2.2 % precision]

R(D^*) hadronic at LHCb

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

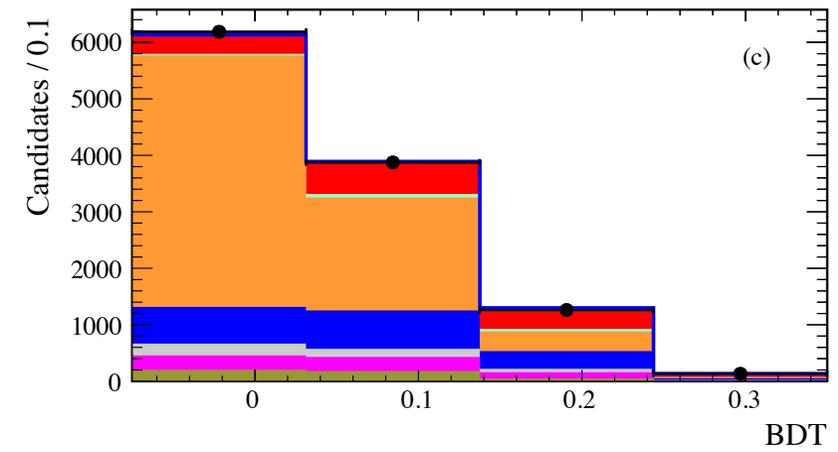
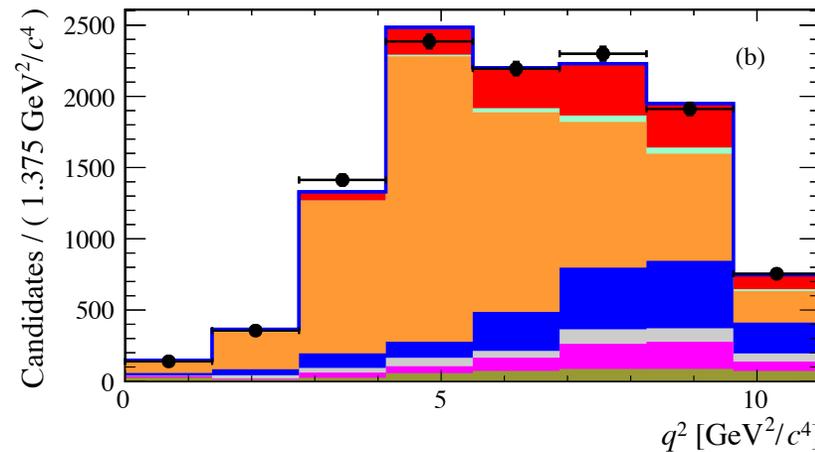
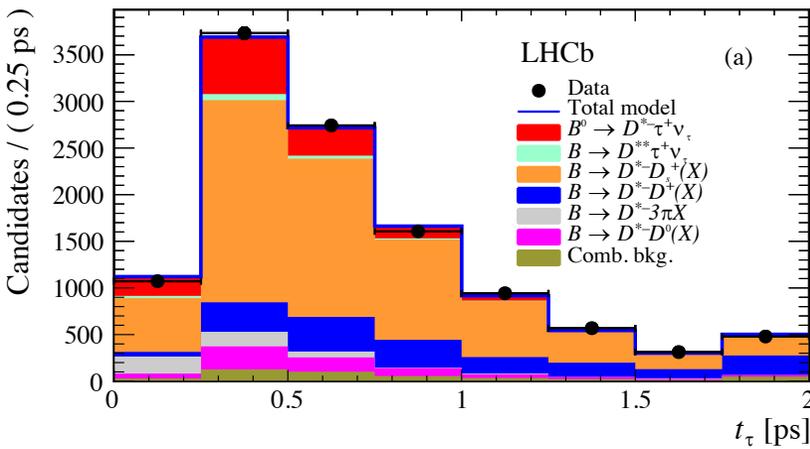


Result:

- $N(B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+)$ unbinned likelihood fit to $M(D^{*-} \pi^+ \pi^- \pi^+)$
- $N(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)$ three dimensional binned fit to data

Variables: τ decay time, q^2 , BDT output

[Run 1 data]



$$K(D^*) = 1.93 \pm 0.12(stat) \pm 0.17(syst)$$

Updated by HFLAV

$$R(D^*) = 0.280 \pm 0.018(stat) \pm 0.029(syst)$$

$\sim 1 \sigma$ from SM

[HFLAV 2019]

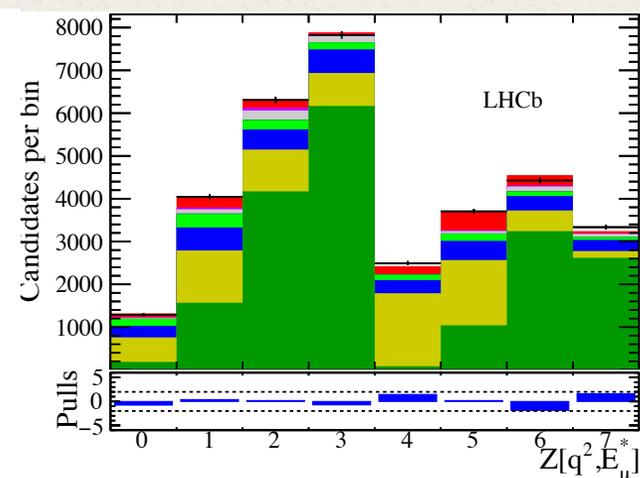
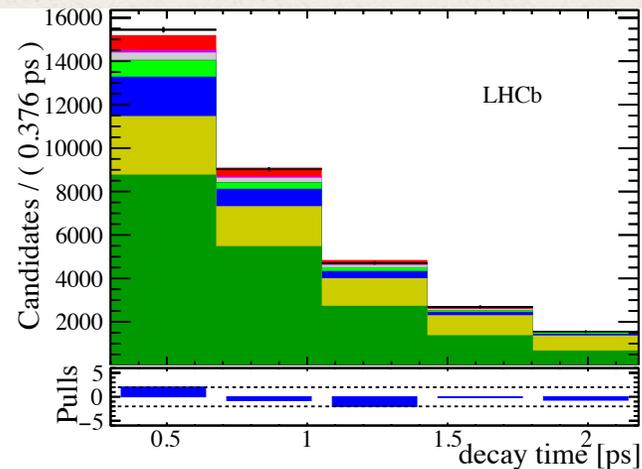
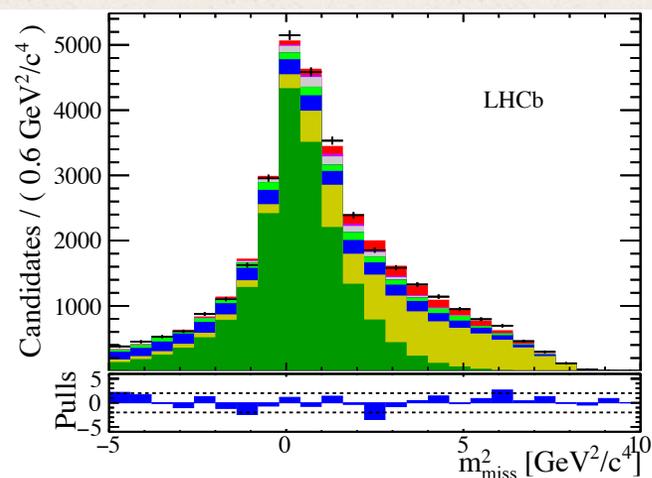
$R(J/\psi)$ muonic at LHCb

Generalization of $R(D^*)$ in the B_c sector, with $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$

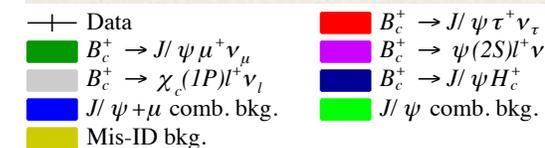
- Form factors unconstrained experimentally.
Significant uncertainties from theory

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

Result: 3D binned maximum likelihood fit to data. Variables: m_{miss}^2 , decay time, $Z(E_\mu, q^2)$



[Run 1 data]



$$R(J/\psi) = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst})$$

$$R_{SM}(J/\psi) \in [0.25, 0.28]$$

~2 σ from SM

[PLB 452 (1999) 129]

[arXiv:0211021]

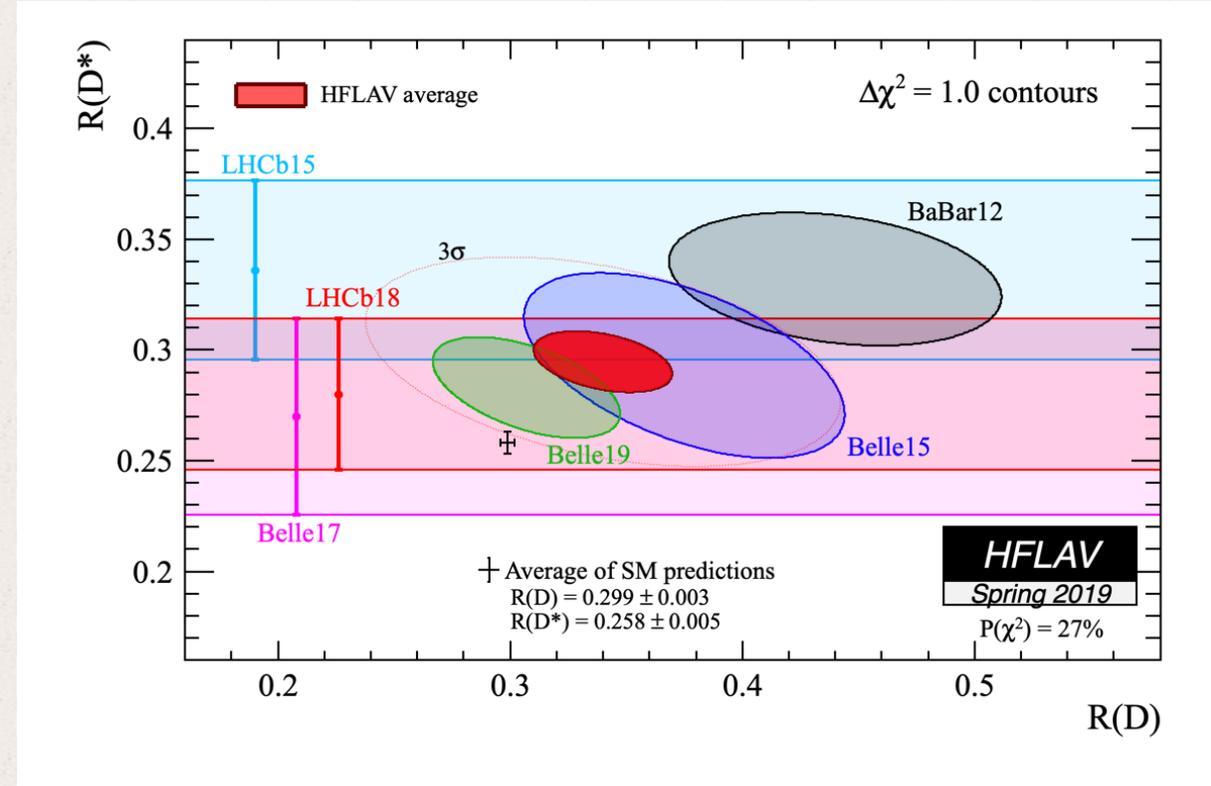
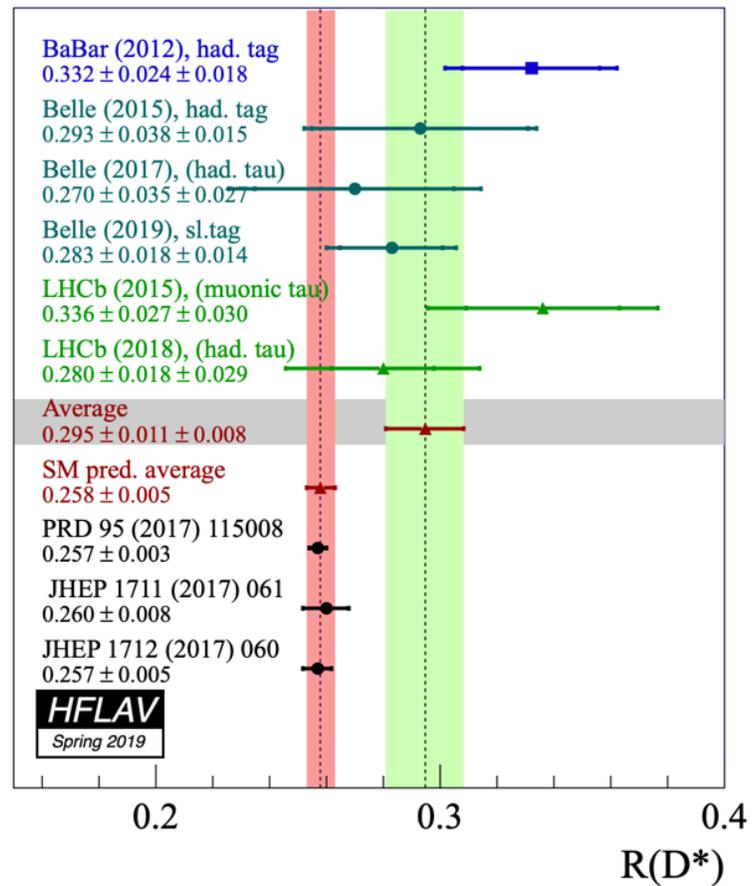
[PRD 73 (2006) 054024]

[PRD 74 (2006) 074008]

[arXiv:2007.06956]

$R(D^{(*)})$ global picture

❖ $R(D^*)$ world average is in tension with the SM at the level of 2.5σ



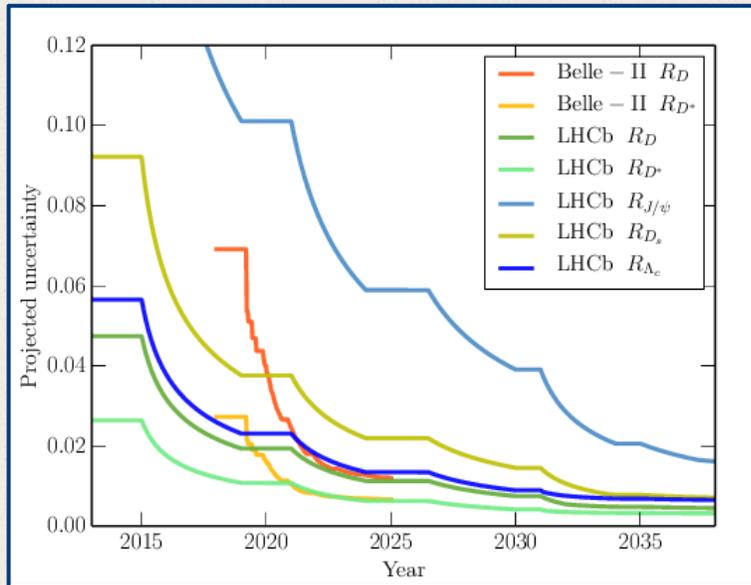
❖ WA combination of $R(D)$ and $R(D^*)$ is in tension with SM at the 3.08σ level

Future prospects

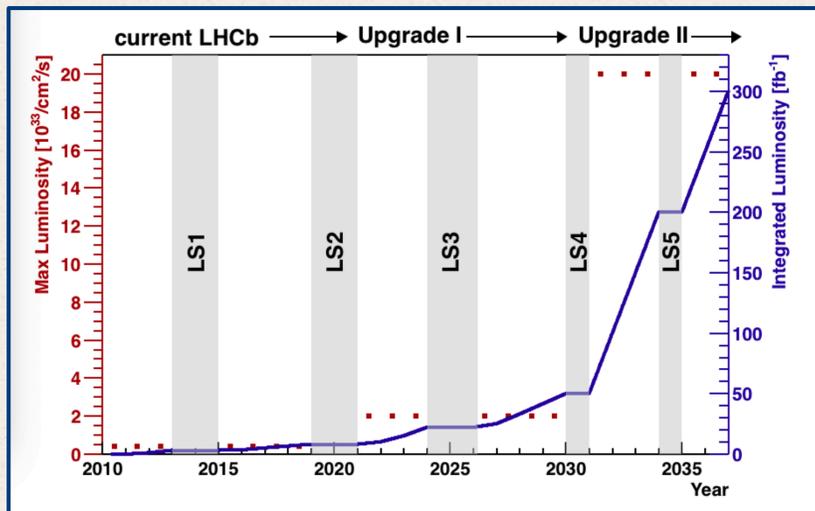
❖ New results are expected from:

- Run 2 updates with a total uncertainty reduction
- Ongoing analyses:
 - $R(D^0): B^+ \rightarrow D^0 \tau \nu$
 - $R(D^+): \bar{B}^0 \rightarrow D^+ \tau \nu$
 - $R(D_S^{(*)}): B_S \rightarrow D_S^{(*)} \tau \nu$
 - $R(D^{**}): B^+ \rightarrow D^{**} (2420)^0 \tau \nu$
 - $R(\Lambda_c^{(*)}): \Lambda_b \rightarrow \Lambda_c^{(*)} \tau \nu$
 - $R(J/\psi): B_c^+ \rightarrow J/\psi \tau \nu$
 - $R(p): \Lambda_b \rightarrow p \tau \nu$
 - Combined measurement of $R(D)$ and $R(D^*)$
- Form factor measurements
 - $\Lambda_b \rightarrow \Lambda_c l \nu$
 - $\Lambda_b \rightarrow \Lambda_c^* l \nu$
 - $B_S \rightarrow D_S^{(*)} l \nu$ [arXiv:2003.08453]
- Angular analyses

❖ In the **Upgrade I**, LHCb will collect $\sim 50 \text{fb}^{-1}$ (luminosity $\times 5$)



[arXiv:1809.06229]

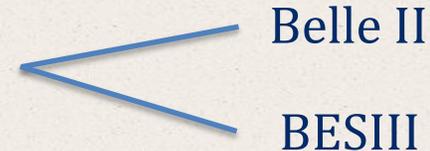


[arXiv:1808.08865]

LFUV road to new physics!

Intriguing tensions with SM in ratios of branching fractions in $b \rightarrow c/\nu$ decays

- ❖ Presented the latest LHCb results on LFU using Run 1 data
- ❖ 9 fb^{-1} recorded at the end of Run 2. Exciting program ahead!
- ❖ Systematic uncertainties:
 - Many are assumed to scale with the accumulated statistics at the LHCb upgrade
 - Others will be improved with external measurements

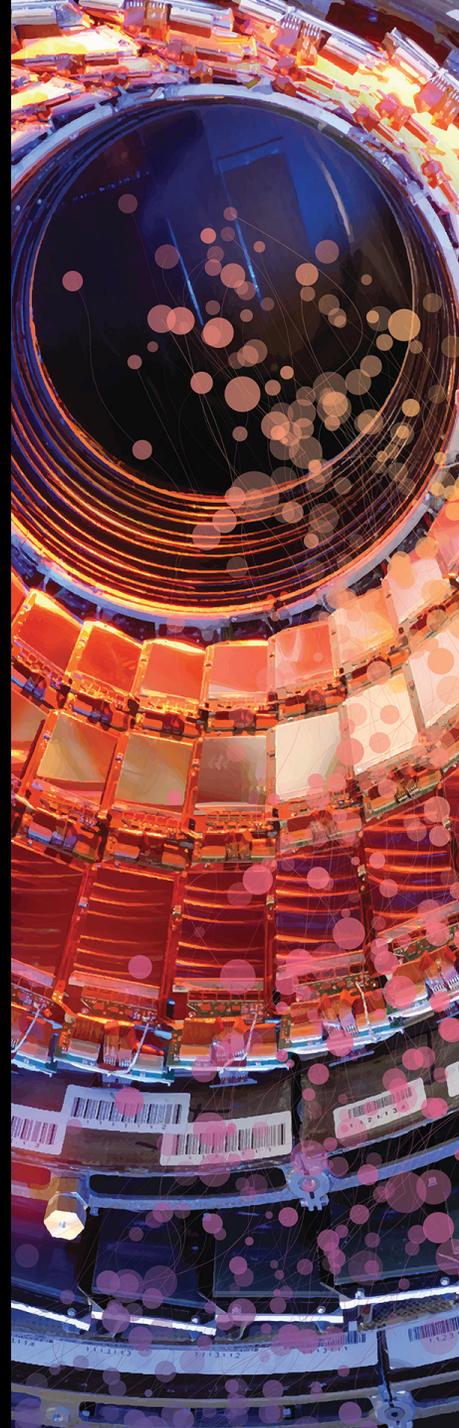


STAY TUNED!



Thank you for
your attention!

Back-up slides



LHCb detector

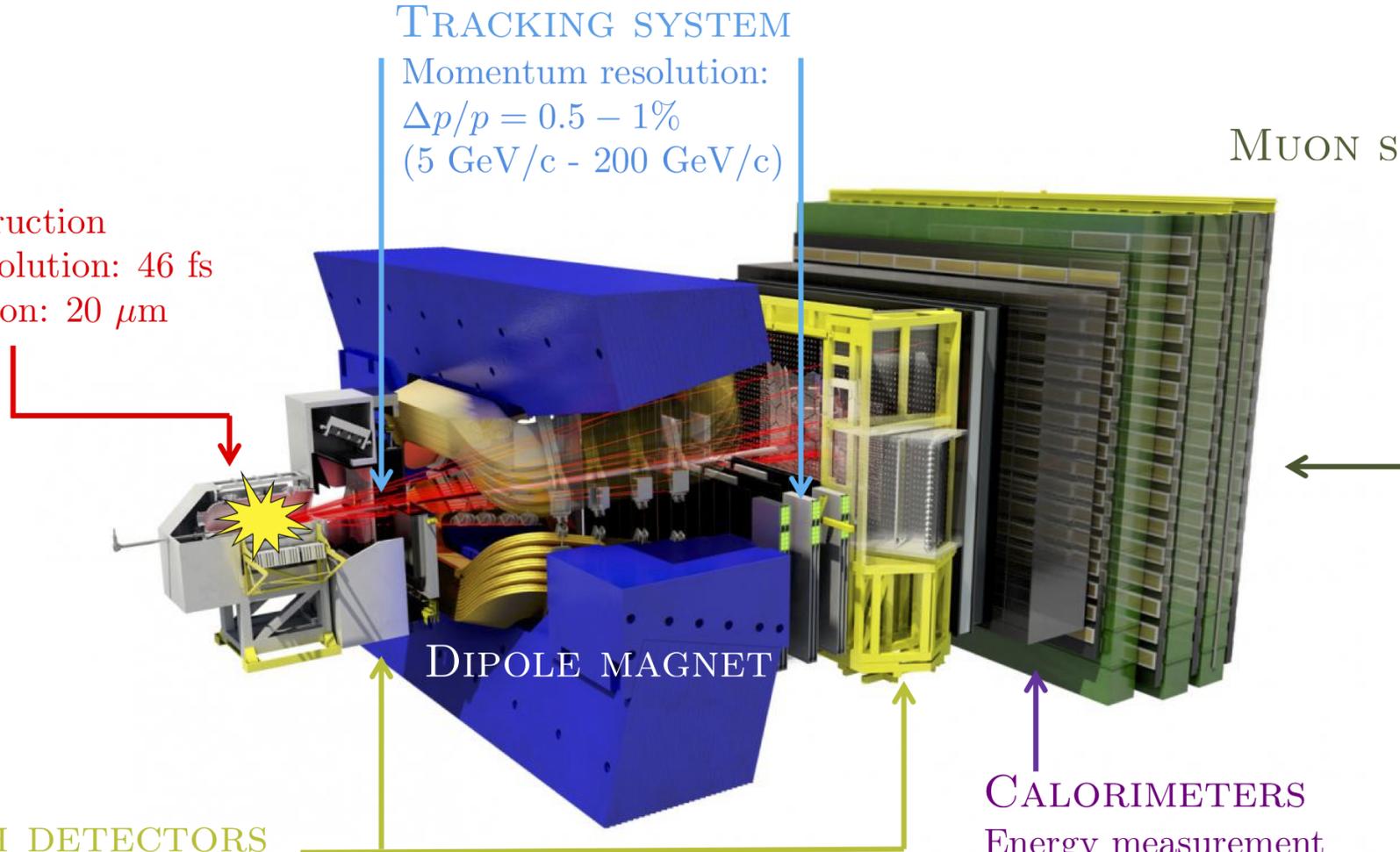
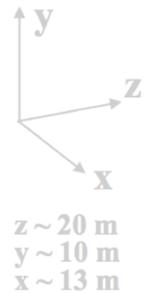
VELO

Vertex reconstruction
Decay time resolution: 46 fs
IP reconstruction: 20 μm

TRACKING SYSTEM

Momentum resolution:
 $\Delta p/p = 0.5 - 1\%$
(5 GeV/c - 200 GeV/c)

MUON SYSTEM



RICH DETECTORS
K/ π /p separation

CALORIMETERS
Energy measurement
Particle identification

LHCb upgrade in a nutshell

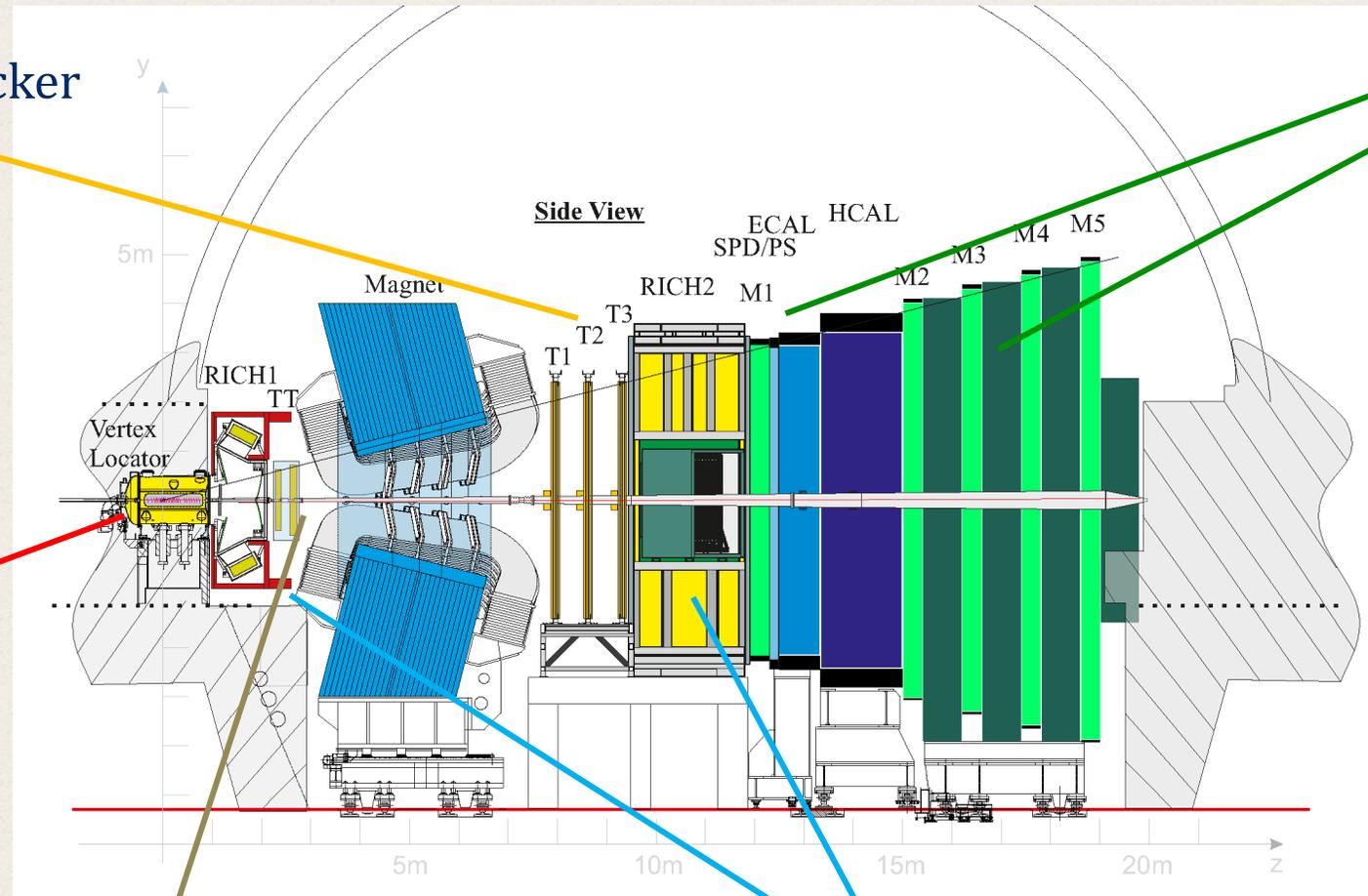
New scintillating fibre tracker

New electronics

New pixel vector detector

New silicon upstream tracker

New optics and photodetectors



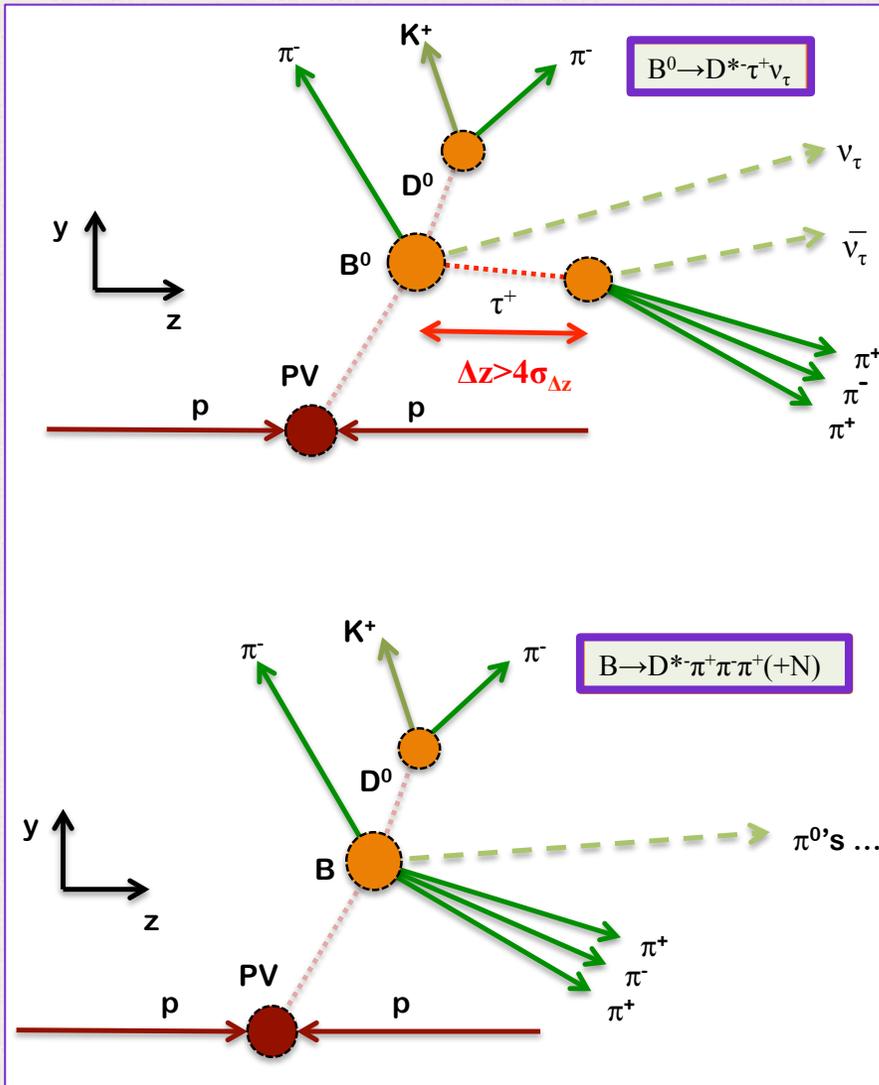
R(D^*) muonic at LHCb

Systematics:

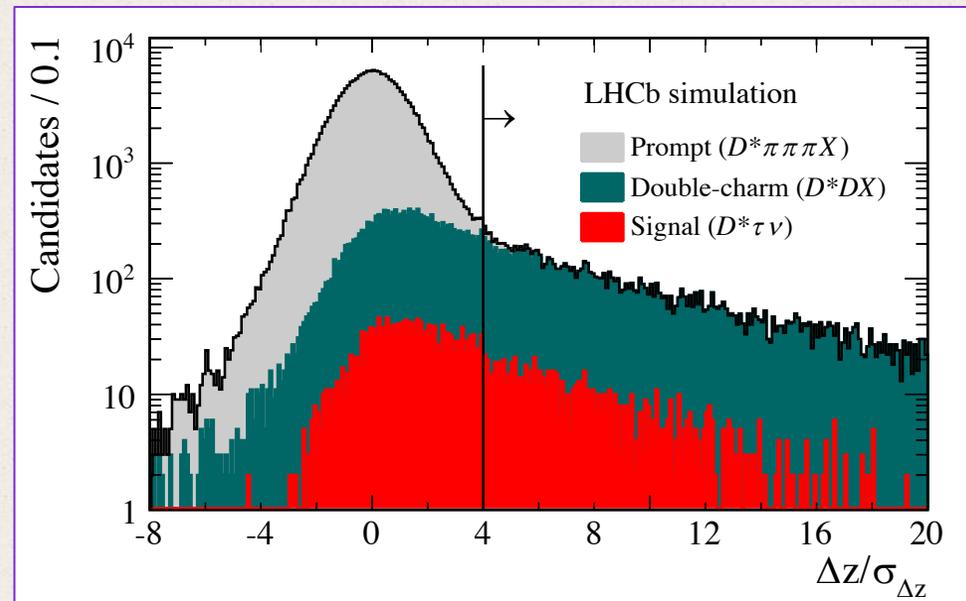
Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\bar{B}^0 \rightarrow D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors	0.6
$\bar{B} \rightarrow D^{*+}H_c(\rightarrow \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\bar{B} \rightarrow D^{**}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \rightarrow D^{**}\mu^-\bar{\nu}_\mu)$	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^*) hadronic at LHCb

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



- Largest background due to $B \rightarrow D^{*-} \pi^+ \pi^- \pi^+ X$, where 3 pions come from the B vertex (100 higher than the signal)
 - Requirement: decay topology with minimum distance between B and τ vertices: $\Delta z > 4 \sigma_{\Delta z}$
 - **Suppressed by 3 orders of magnitude**
- 2nd largest background is the double charm $B \rightarrow D^{*-} D_s^+ X$:
Multivariate Analysis (BDT)

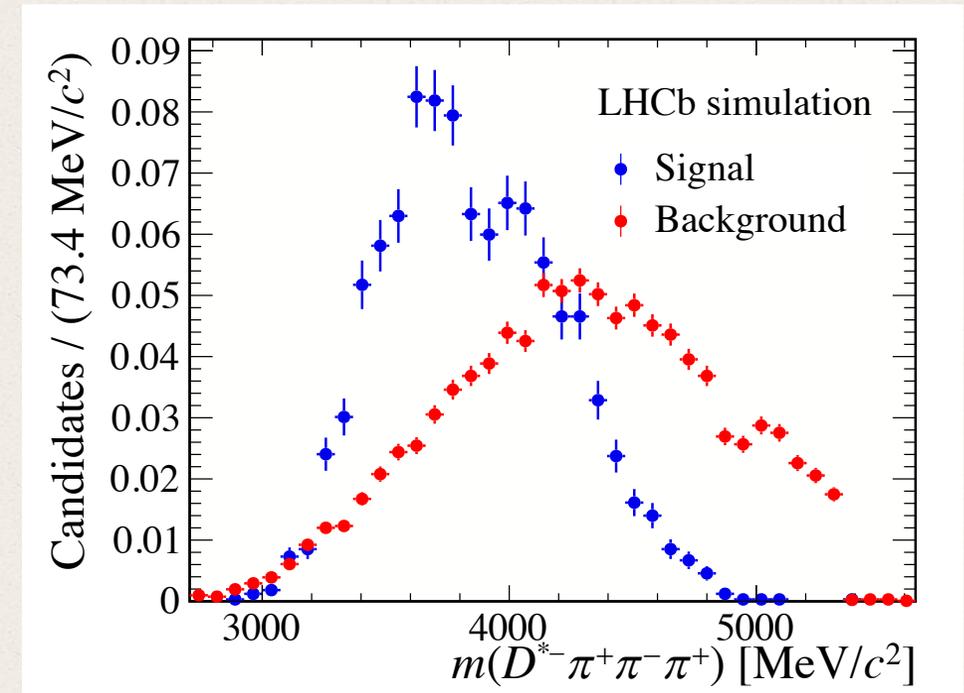
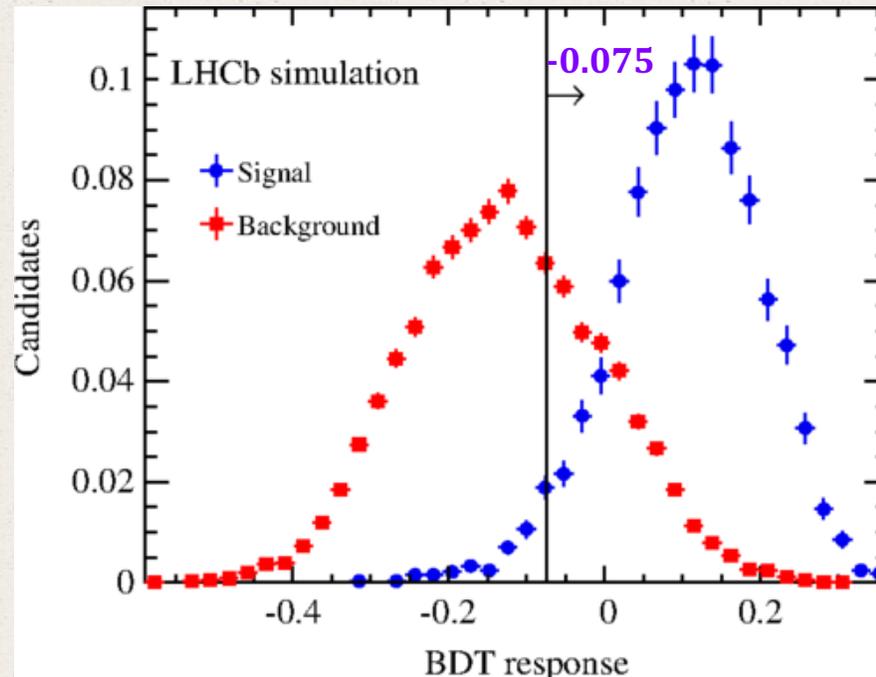


$R(D^*)$ hadronic at LHCb

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



- Most important background after the inversion cut comes from $B \rightarrow D^* D_s^+ X$
- Multivariate Analysis: 18 variables combined in a **BDT**:
 - 3 π variables
 - $D^* 3\pi$ dynamics
 - Neutral isolation variables



BDT used as variable in the fit to extract signal yield

R(D^*) hadronic at LHCb

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



Systematics:

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
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
Normalization channel	1.0
Particle identification	1.3
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
Form factors (efficiency)	1.0
Total uncertainty	9.1

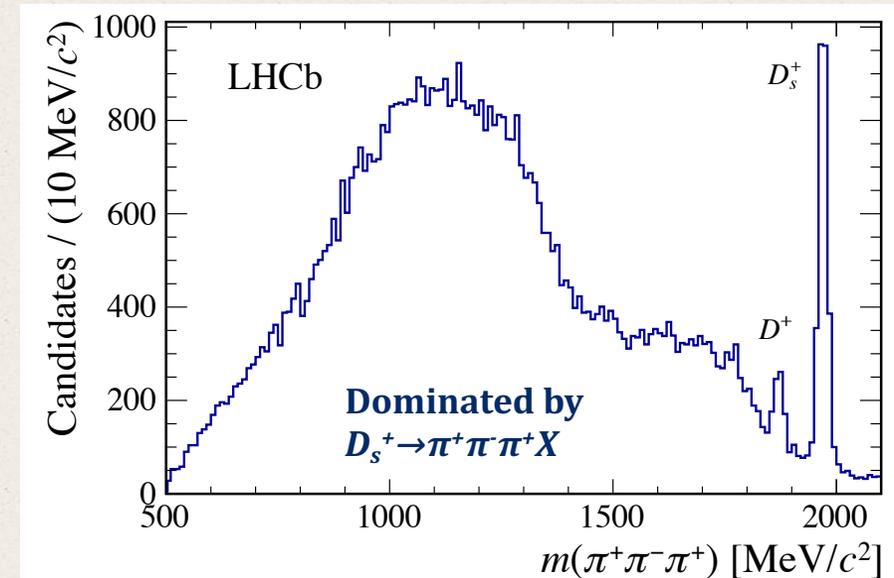
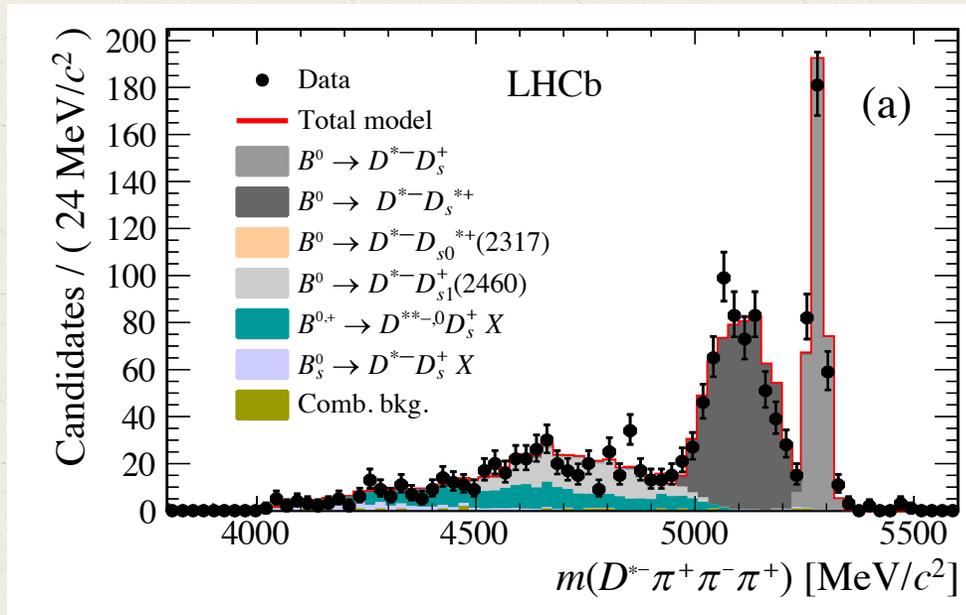
R(D^*) hadronic at LHCb

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



Main systematic uncertainties due to:

- Size of **simulated simple**
- Shape of the **background $B \rightarrow D^* D_s X$**
- $D_{(s)}^+ \rightarrow \pi^+ \pi^- \pi^+ X$ decay mode. **BESIII** future measurement will reduce this uncertainty. Improvement as well of the upgraded ECAL
- Branching fraction of normalisation mode $B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+$ known with $\sim 4\%$ precision. **Belle II** can measure it precisely



R(J/ψ) hadronic at LHCb

Systematics:

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