

Study of Lepton Violation Universality with semitauonic decays in LHCb

Status and Prospects

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on behalf of the LHCb Collaboration
FPCP 2023

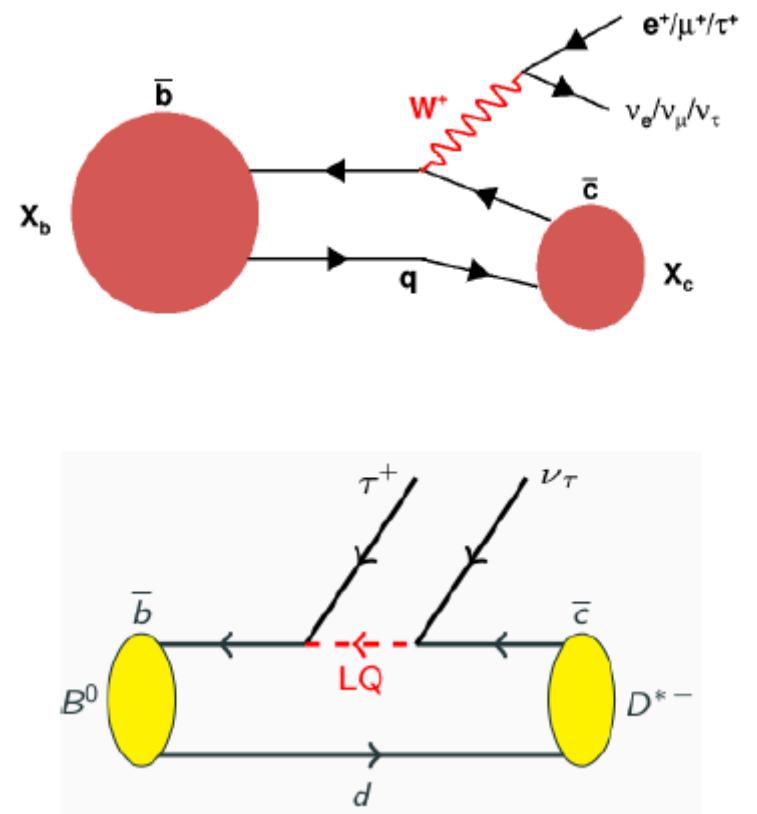
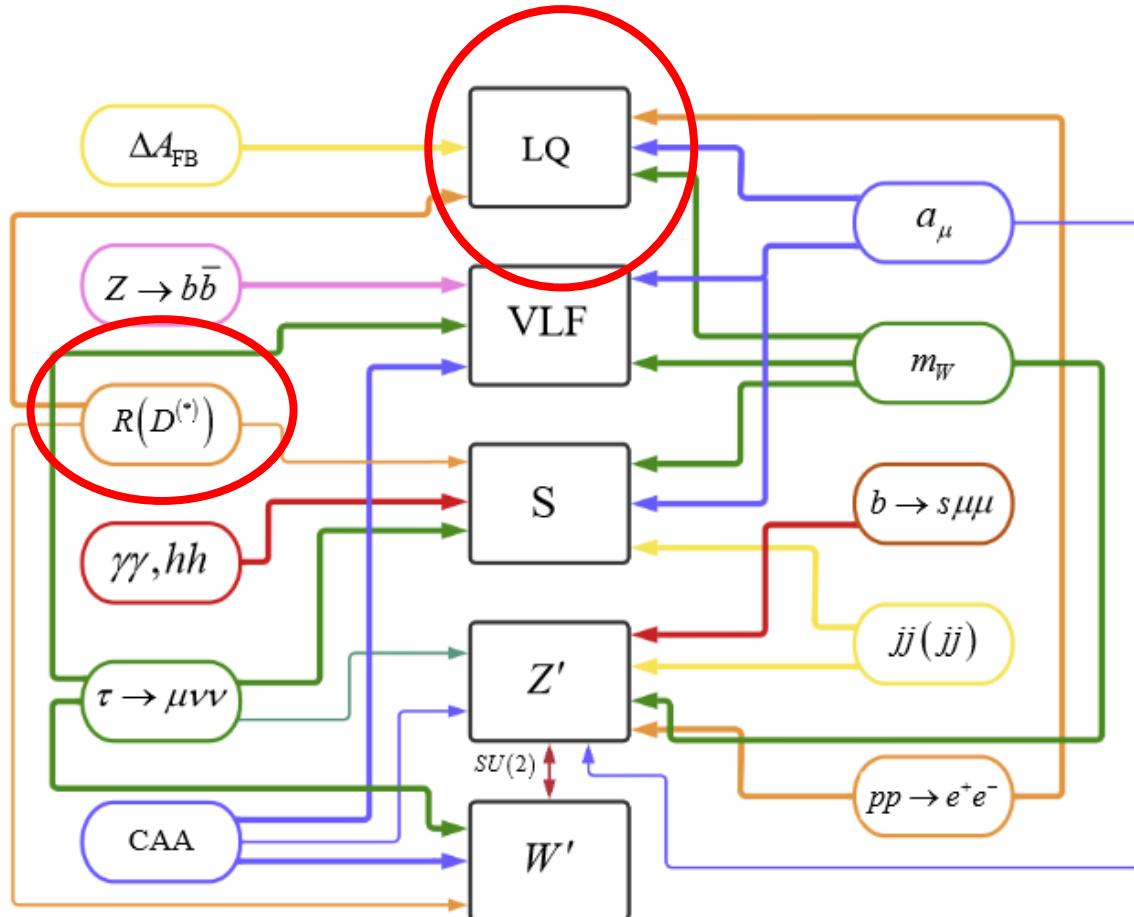


Lepton Flavour Universality

- Lepton Flavour Universality is one of many « ad hoc » symmetries and « pillars » of the Standard Model
 - Baryon number, lepton number, (charged) lepton flavour,...
- It postulates that the properties of the three charged leptons (e, μ, τ) are exactly the same beside their mass. This does not need to be the case in many New Physics models
- First hints of Lepton Flavour Universality violation appeared 10 years ago with BABAR publication regarding semi-tauonic B decays. This field became « the hottest game » in town with results coming both from charged and neutral currents

Panorama of SM anomalies

A. Crivellin , arxiv:hep-ph 2304.01694



$R(D^{(*)})$ measurements in LHCb

$$R(D) = BR(B \rightarrow D\tau\nu) / BR(B \rightarrow D\mu\nu)$$

$$\tau^- \rightarrow \mu^- \nu_\tau \nu_\mu$$

$$\tau^- \rightarrow \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$$

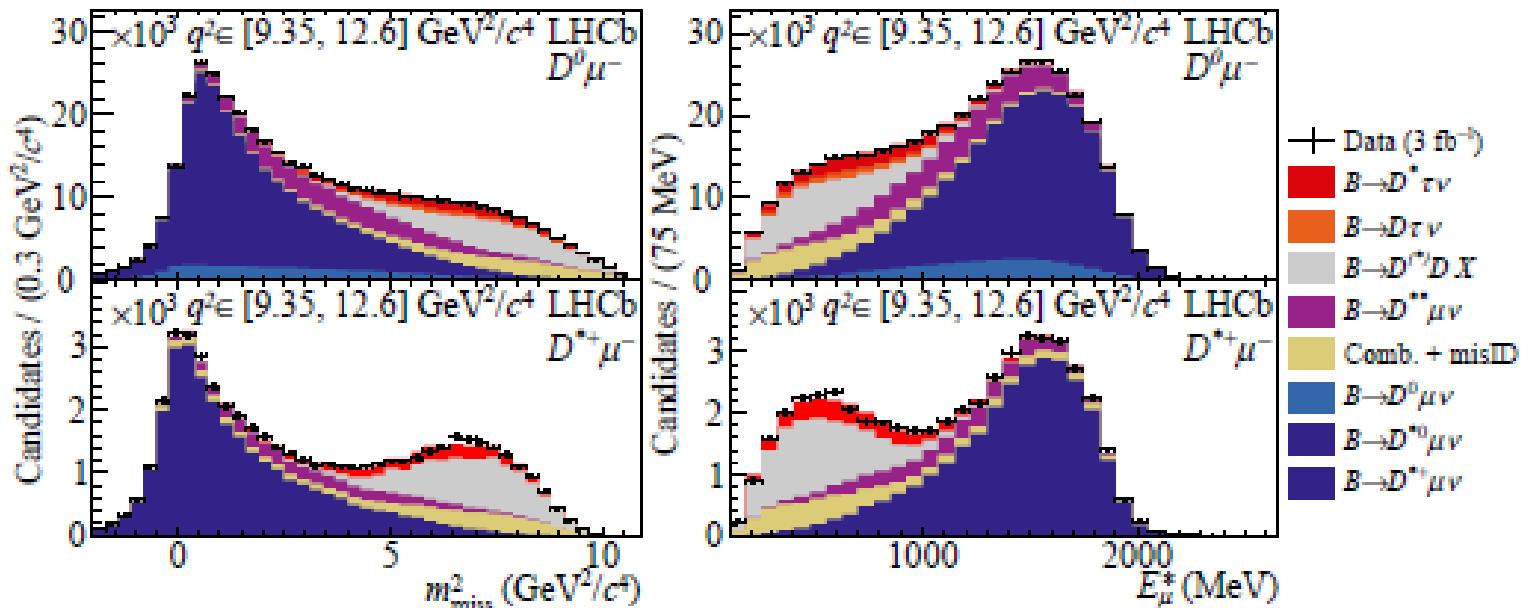
- Pros
 - Direct measurement of $R(D, D^*)$
 - High statistics
- Cons
 - Double charm background control must be very good (**mostly D^+**)
 - Sensitive to $D^{**} \mu^- \nu_\mu$
- Pros
 - The possibility to measure the τ vertex is the key to reject the background and obtain a high purity sample
 - The 3π dynamics of the τ decay is very specific : possible to distinguish τ decays from the main double charm background **from D_s decays**
- Cons
 - Access to $R(D)$ requires an external BR
 - Lower statistics

[arXiv:2302.02886] (Submitted to PRL)

- Simultaneous measurement of $R(D)$ and $R(D^*)$ with Run 1 data using muonic $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$

3D template fit to

- $q^2 \equiv (p_B - p_{D^{(*)}})^2$
- $m_{\text{miss}}^2 \equiv (p_B - p_{D^{(*)}} - p_\mu)^2$
- E_μ^* energy of μ



$$R(D) = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{syst})$$

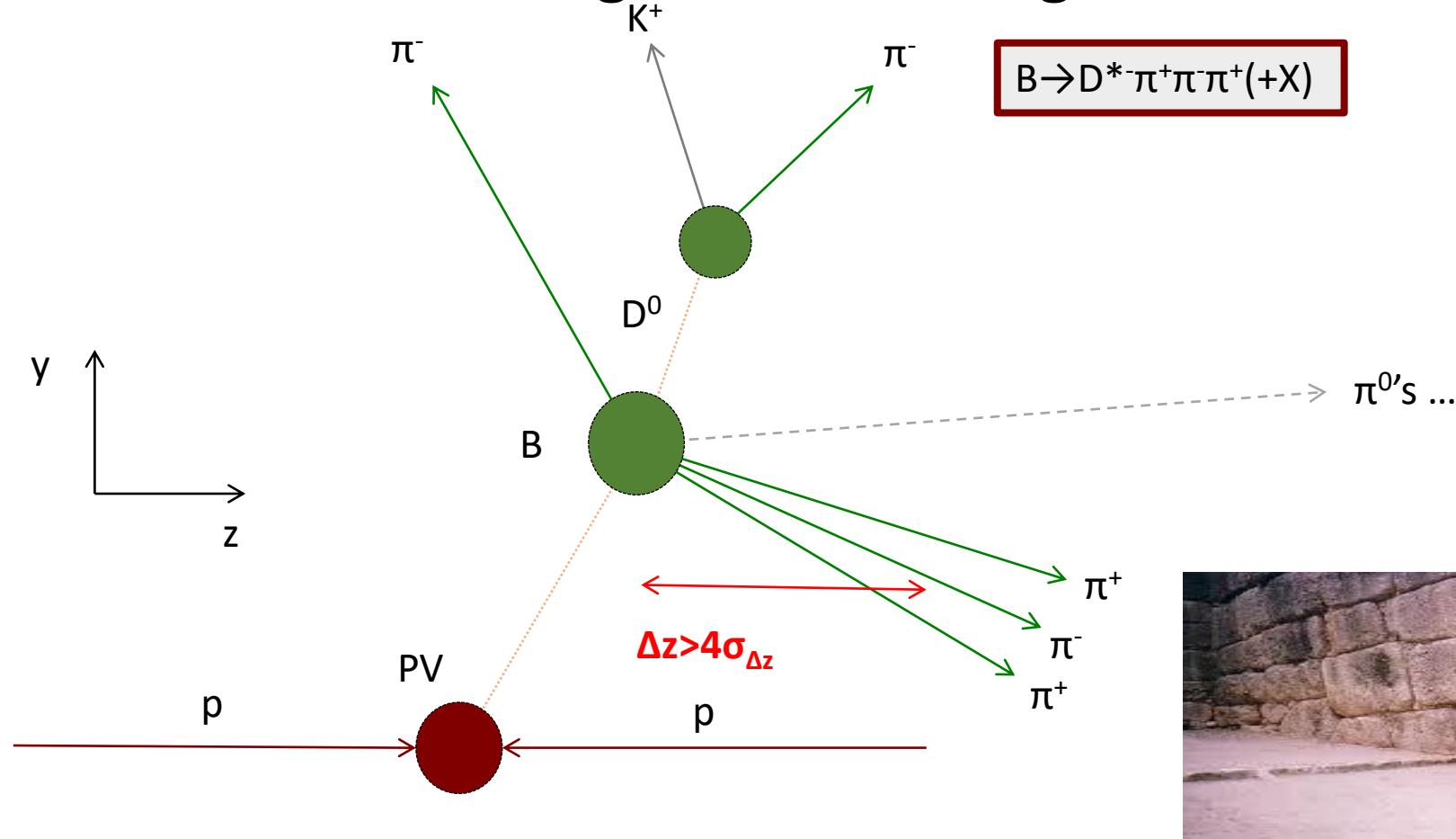
$$R(D^*) = 0.281 \pm 0.018(\text{stat}) \pm 0.023(\text{syst})$$

Agreement with SM at 1.9σ

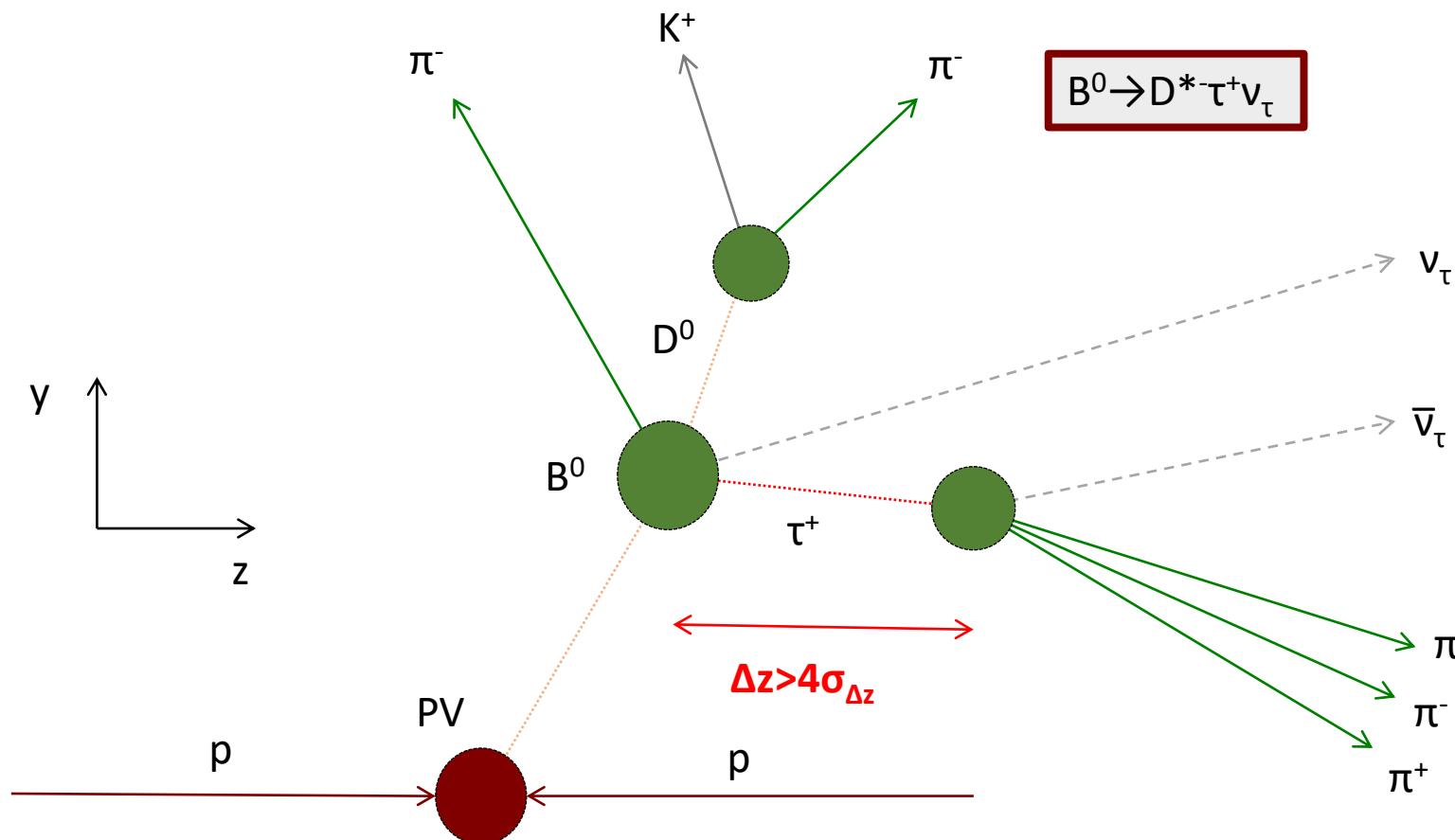
R(D^*) measurement with hadronic τ decays

Vertex topology of the usual B decay

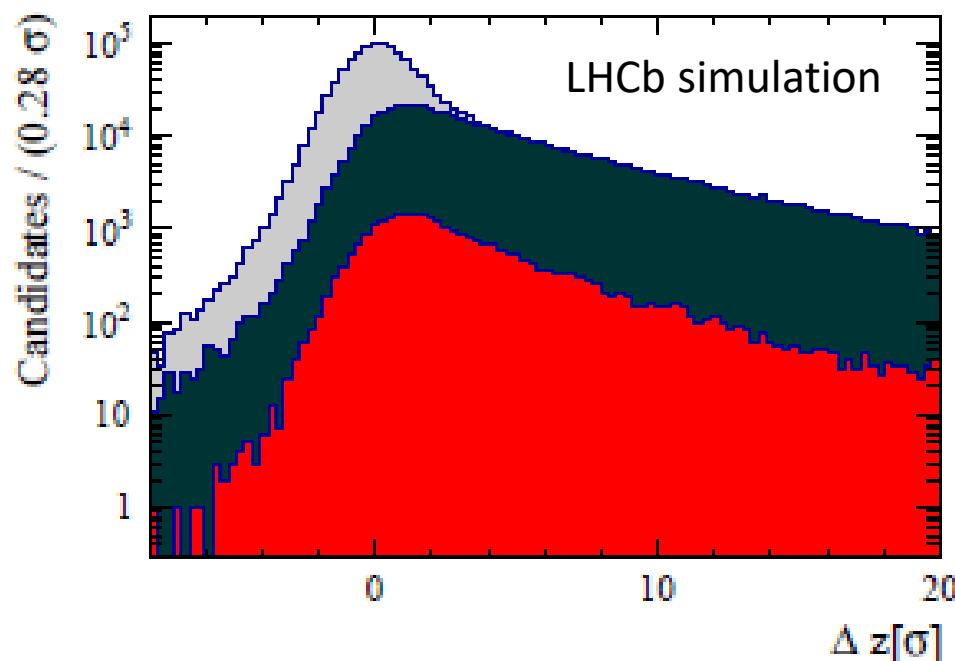
100 times larger than the signal



Selection: detached vertex

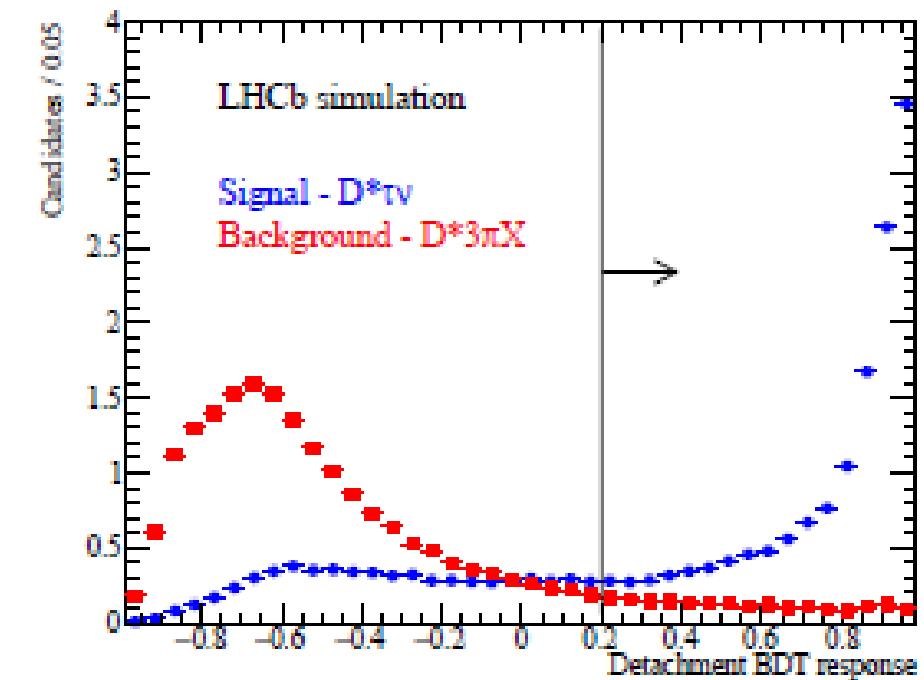


- Suppressed by requiring the τ vertex to be downstream w.r.t. the B vertex along the beam direction - detachment criteria
- A BDT classifier is used along with the vertex separation variables



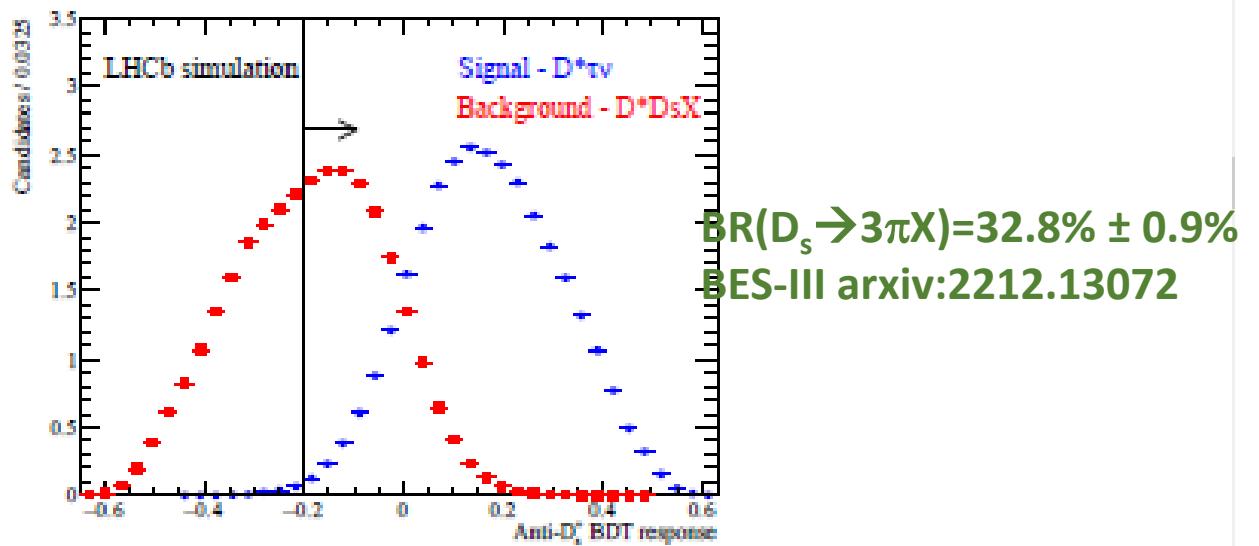
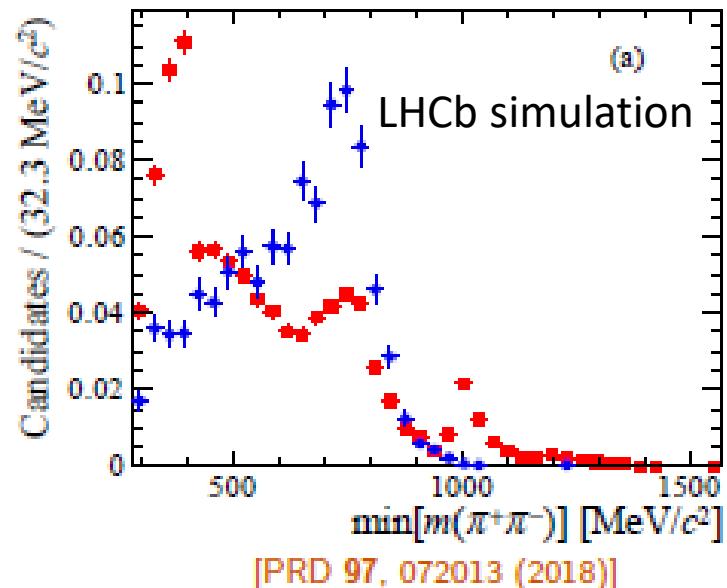
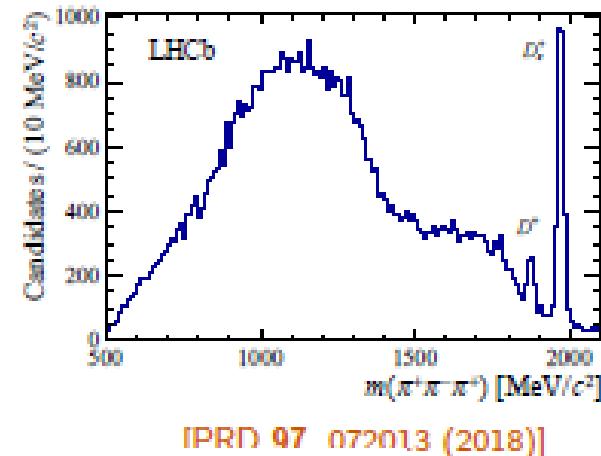
LHCb-PAPER-2022-052
arxiv:2305.01463

Prompt $D^*3\pi X$
Double Charm
Signal

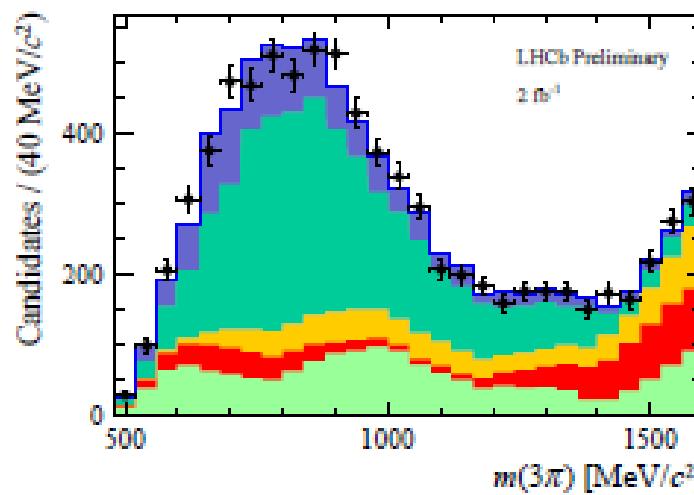
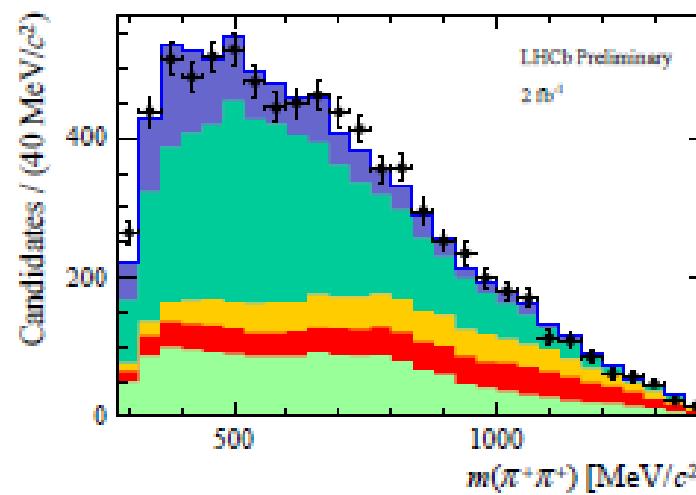
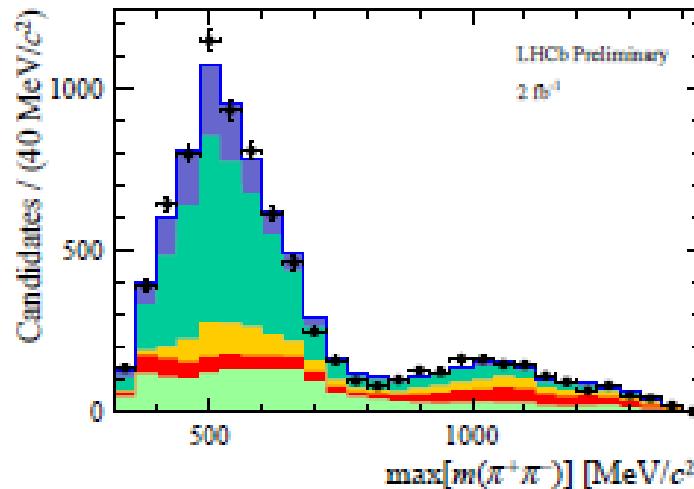
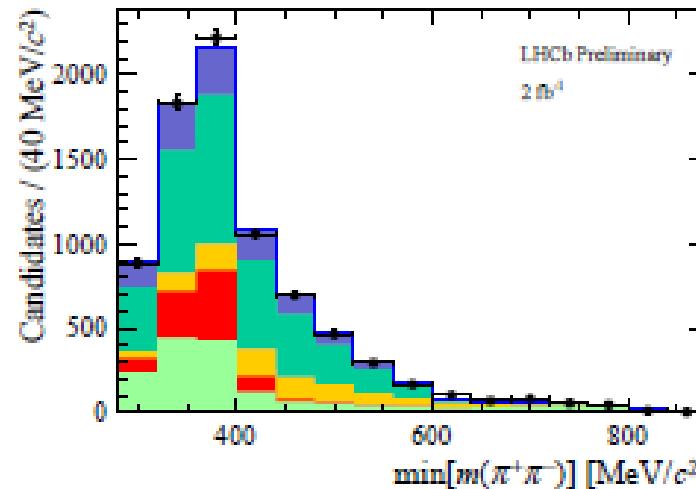


Double-charm backgrounds

- $B \rightarrow D^{*-}(D_s^+, D^+, D^0)X$ backgrounds
- $B \rightarrow D^{*-}D_s^+ X$ the largest contributor
- A BDT classifier based on kinematics and resonant structure to separate signal from $B \rightarrow D^{*-}D_s^+ X$



- This BDT output is one of the fit variables for signal extraction

D_s^+ decay

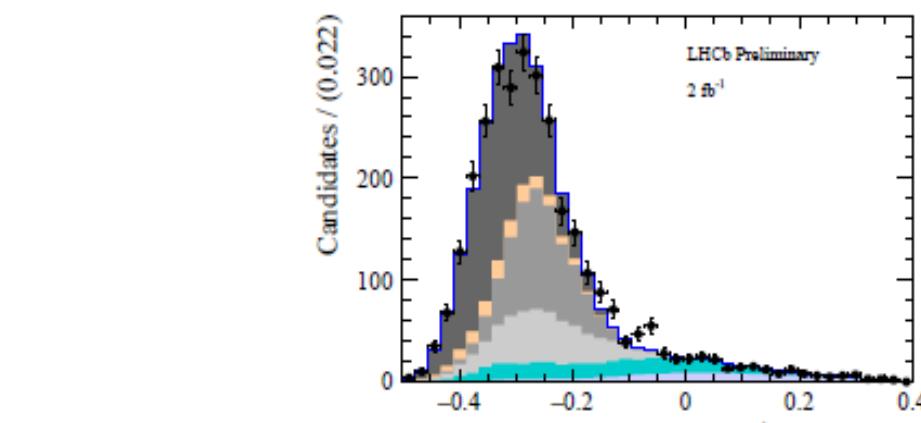
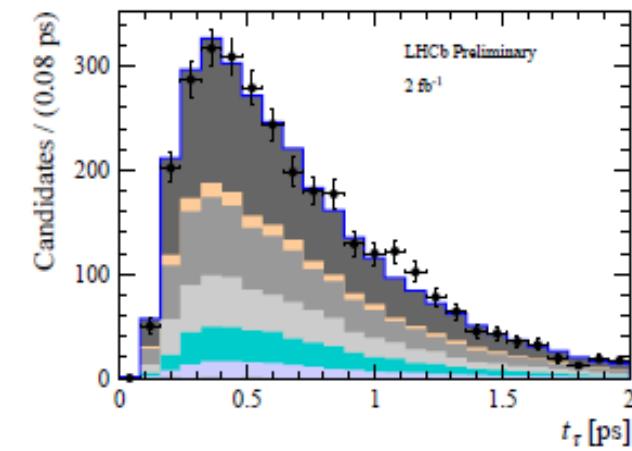
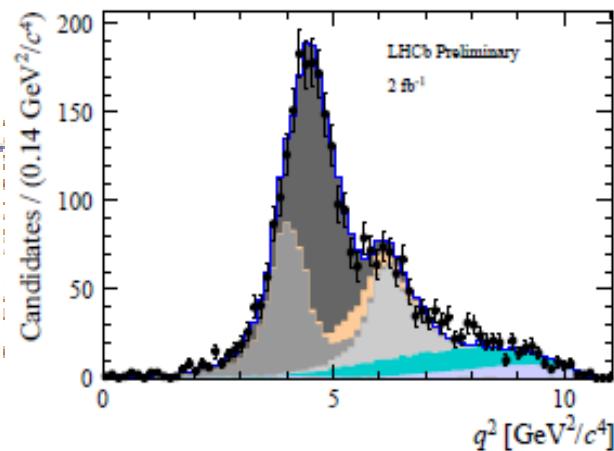
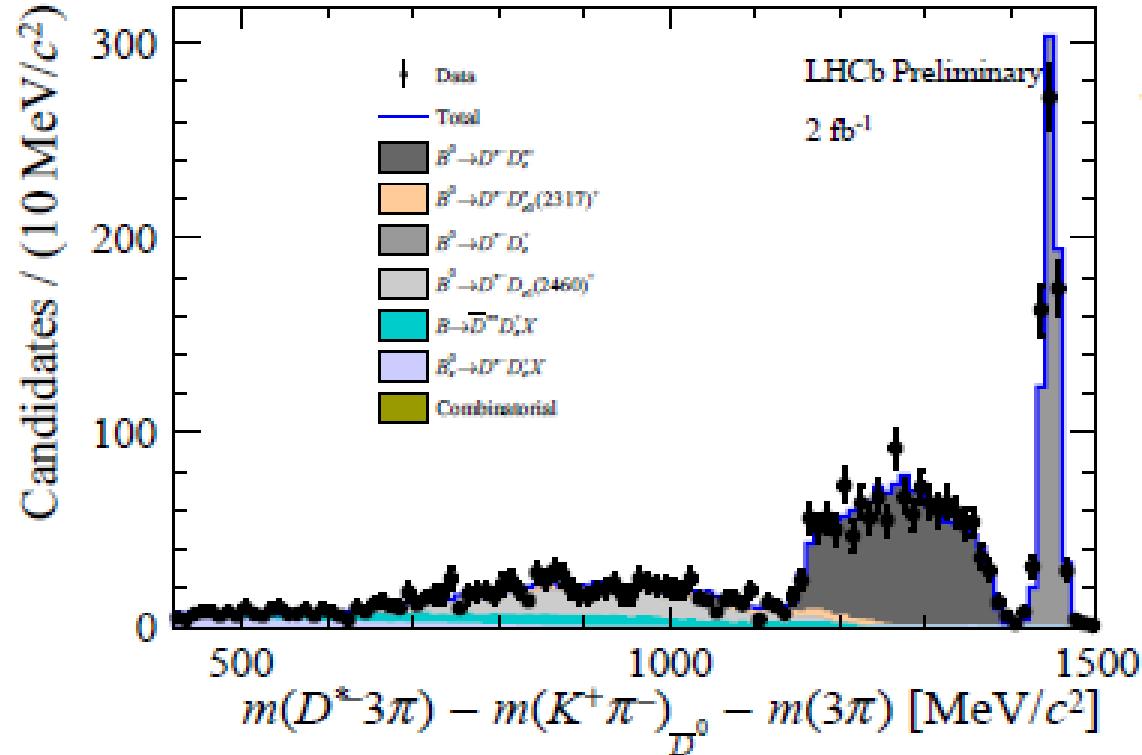
LHCb-PAPER-2022-052
arxiv:2305.01463

- ↑ Data
- Total
- Non- D_s^+ background
- Other D_s^+ modes
- $D_s^+ \rightarrow \{\omega, \phi\} \pi^+(\pi^0)$
- $D_s^+ \rightarrow \eta \pi^+(\pi^0)$
- $D_s^+ \rightarrow \eta' \pi^+(\pi^0)$

- The fractions of various modes extracted and simulation corrected accordingly

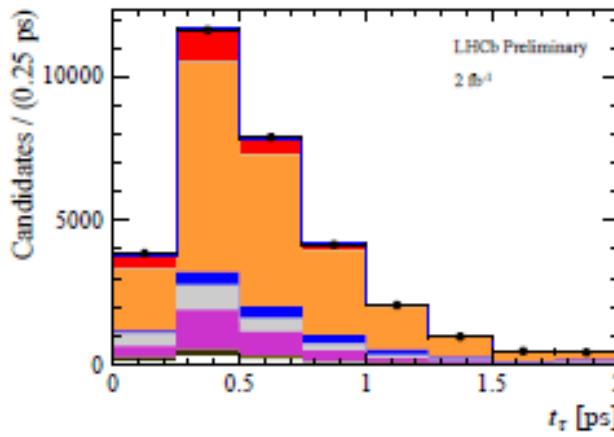
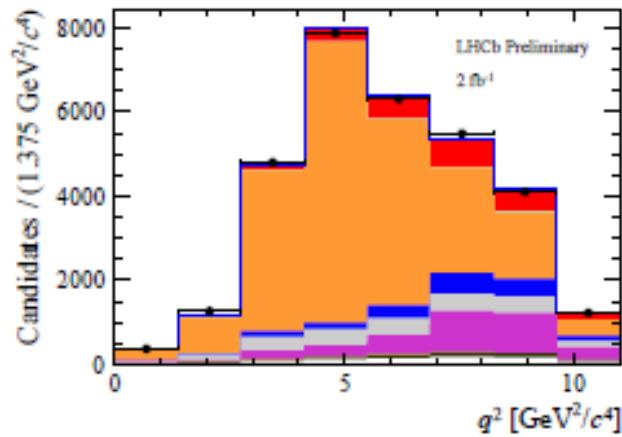
D_s^+ production

LHCb
Preliminary

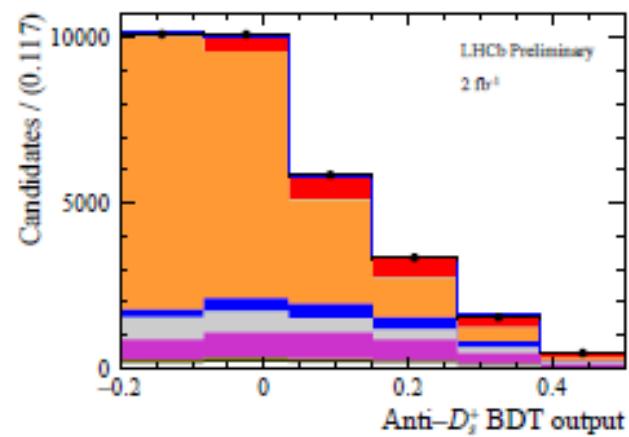


- Fractions of each component determined and used as constraints in the signal extraction fit
- Good agreement between model and data for the fit variables

Signal extraction



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arxiv:2305.01463



- + Data
- Total
- $B^0 \rightarrow D^+ \tau^+ \nu_\tau$
- $B \rightarrow \bar{D}^{**} \tau^+ \nu_\tau$
- $B \rightarrow D^+ D_s^+(X)$
- $B \rightarrow D^* D^+(X)$
- $B \rightarrow D^* 3\pi X$
- $B \rightarrow D^* D^0(X)$
- Comb. B^0
- Comb. \bar{D}
- Comb. D^*

$$N(B^0 \rightarrow D^* \tau^+ \nu_\tau) = 2469 \pm 154$$

Run 1 yield = 1296 ± 86

- ▶ Larger dataset
- ▶ Improved selection

Systematic uncertainties

Source	Systematic uncertainty on $\mathcal{K}(D^*)$ (%)
PDF shapes uncertainty (size of simulation sample)	2.0
Fixing $B \rightarrow D^* - D_s^+(X)$ bkg model parameters	1.1
Fixing $B \rightarrow D^* - D^0(X)$ bkg model parameters	1.5
Fractions of signal τ^+ decays	0.3
Fixing the $\bar{D}^{**}\tau^+\nu_\tau$ and $D_s^{***+}\tau^+\nu_\tau$ fractions	+1.8 -1.9
Knowledge of the $D_s^+ \rightarrow 3\pi X$ decay model	1.0
Specifically the $D_s^+ \rightarrow a_1 X$ fraction	1.5
Empty bins in templates	1.3
Signal decay template shape	1.8
Signal decay efficiency	0.9
Possible contributions from other τ^+ decays	1.0
$B \rightarrow D^* - D^+(X)$ template shapes	+2.2 -0.8
$B \rightarrow D^* - D^0(X)$ template shapes	1.2
$B \rightarrow D^* - D_s^+(X)$ template shapes	0.3
$B \rightarrow D^* - 3\pi X$ template shapes	1.2
Combinatorial background normalisation	+0.5 -0.6
Preselection efficiency	2.0
Kinematic reweighting	0.7
Vertex error correction	0.9
PID efficiency	0.5
Signal efficiency (size of simulation sample)	1.1
Normalisation mode efficiency (modelling of $m(3\pi)$)	1.0
Normalisation efficiency (size of simulation sample)	1.1
Normalisation mode PDF choice	1.0
Total systematic uncertainty	+6.2 -5.9
Total statistical uncertainty	5.9

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arxiv:2305.01463

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi^\pm)} = 1.700 \pm 0.101(\text{stat})^{+0.105}_{-0.100}(\text{syst})$$

- The absolute branching fraction of $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$ decays

$$\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau) = (1.23 \pm 0.07 \text{ (stat)} \pm 0.08 \text{ (syst)} \pm 0.05 \text{ (ext)}) \times 10^{-2}$$

$$R(D^*) = \mathcal{K}(D^*) \frac{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi^\pm)}{\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)}$$

- The BFs of $B^0 \rightarrow D^{*-} 3\pi^\pm$ and $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$ - external inputs

$$R(D^*) = 0.247 \pm 0.015(\text{stat}) \pm 0.015(\text{syst}) \pm 0.012(\text{ext})$$

In agreement with Run 1 result

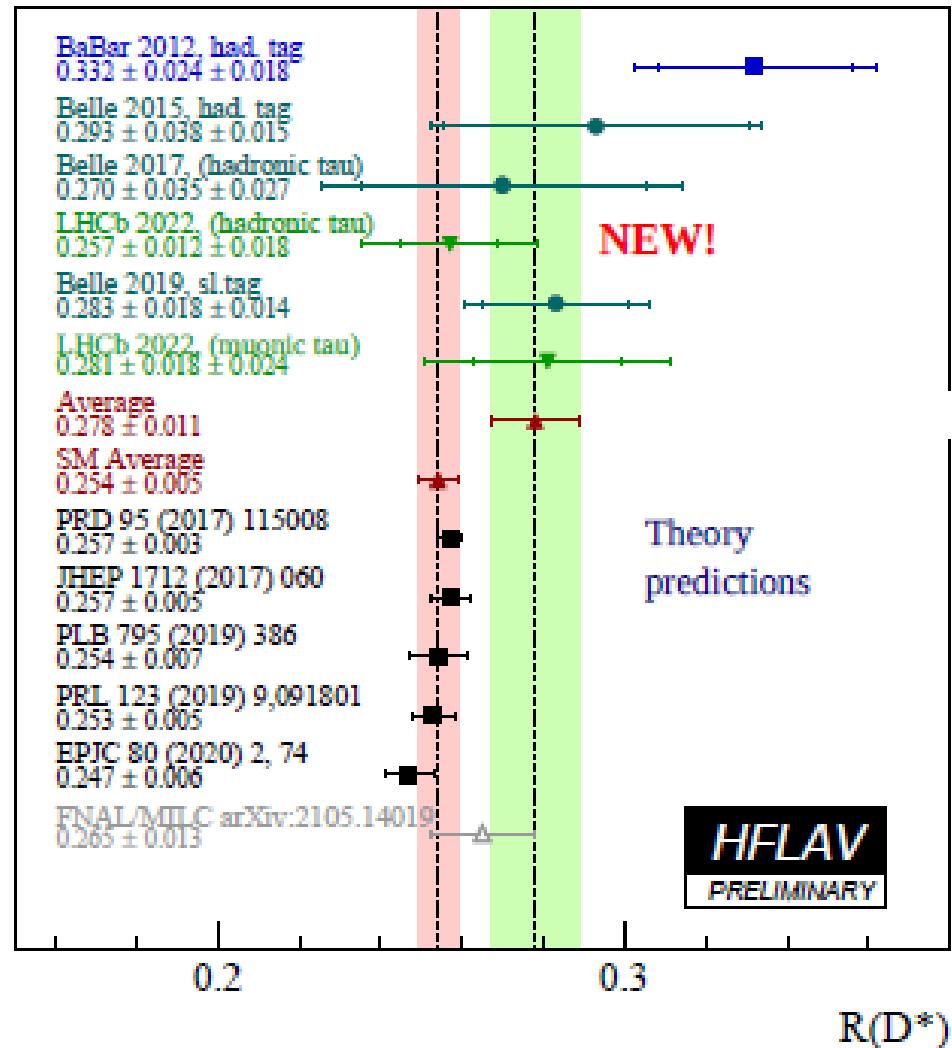
- Combining with the Run 1 result

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arxiv:2305.01463

$$R(D^*)_{2011-2016} = 0.257 \pm 0.012 \text{ (stat)} \pm 0.014 \text{ (syst)} \pm 0.012 \text{ (ext)}$$

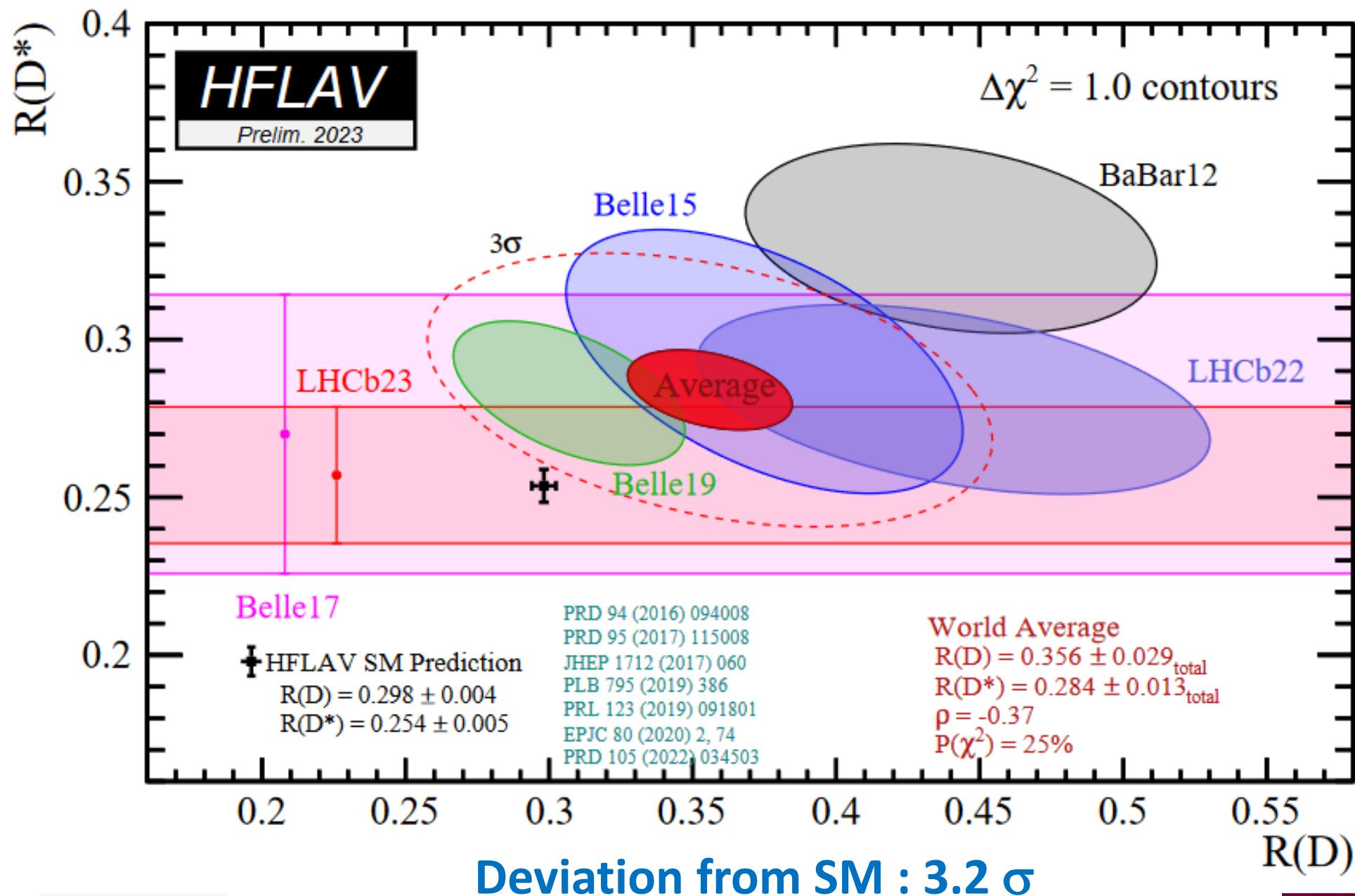
Agreement within 1σ to SM

$$R(D^*)_{\text{SM}} = 0.254 \pm 0.005 \text{ [HFLAV]}$$



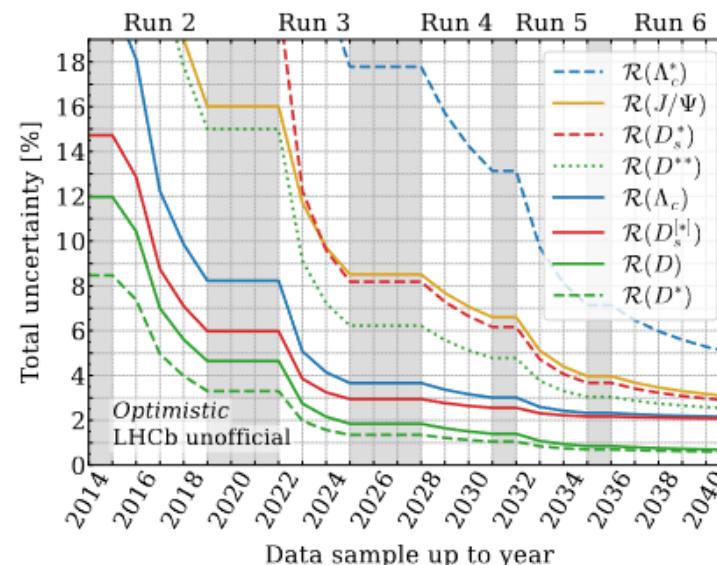
LHCb-PAPER-2022-052
arxiv:2305.01463

- One of the most precise measurements of $R(D^*)$



Semitauonic prospects in LHCb

- Many more semitauonic results expected soon using the **muonic** and **hadronic** τ decay channel :
 - D^* polarization measurement
 - $\mathcal{R}(D^*)$, $R(D^\circ)$, $R(D^+)$ using the full Run2 data
 - $\mathcal{R}(D^+)$
- Work is also ongoing on $\mathcal{R}(D_s)$, $\mathcal{R}(J/\psi)$, full angular analysis



Rev. Mod. Phys. 94, 015003 (2022)

Conclusions

- New simultaneous measurement of $R(D)$ and $R(D^*)$ using muonic channel

$$R(D^*) = 0.281 \pm 0.018 \pm 0.024 \quad \text{LHCb-PAPER-2022-039}$$

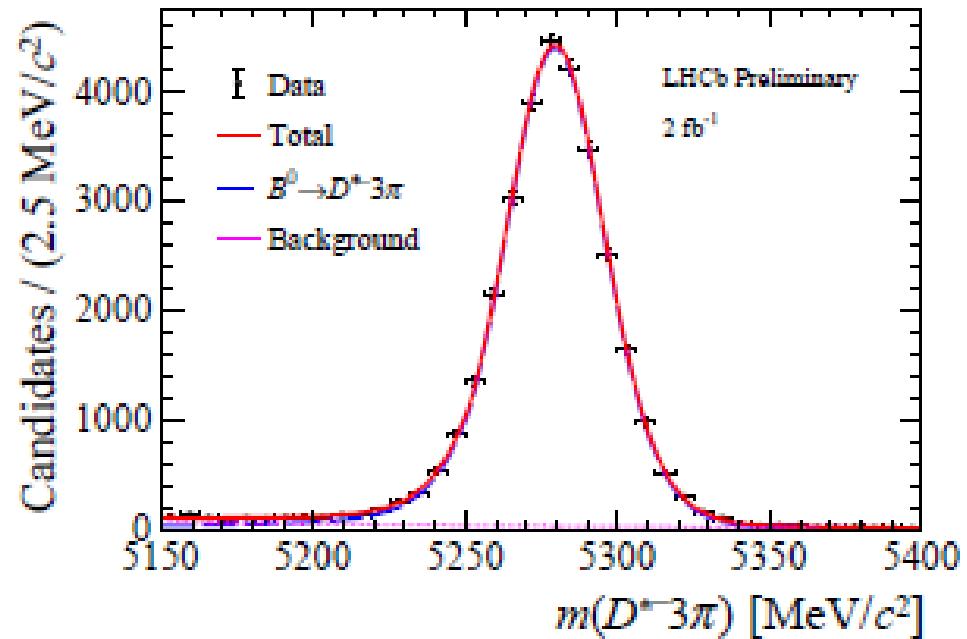
$$R(D) = 0.441 \pm 0.060 \pm 0.066 \quad \text{arXiv:2302.02886}$$

- New updated measurement of $R(D^{*+})$ LHCb-PAPER-2022-052
arxiv:2305.01463

$$R(D^*)_{2011-2016} = 0.257 \pm 0.012 \text{ (stat)} \pm 0.014 \text{ (syst)} \pm 0.012 \text{ (ext)}$$

- Discrepancy level between new WA and SM prediction 3.2σ
 - « Le canard est toujours vivant »
- Compatible with SM and with the present WA

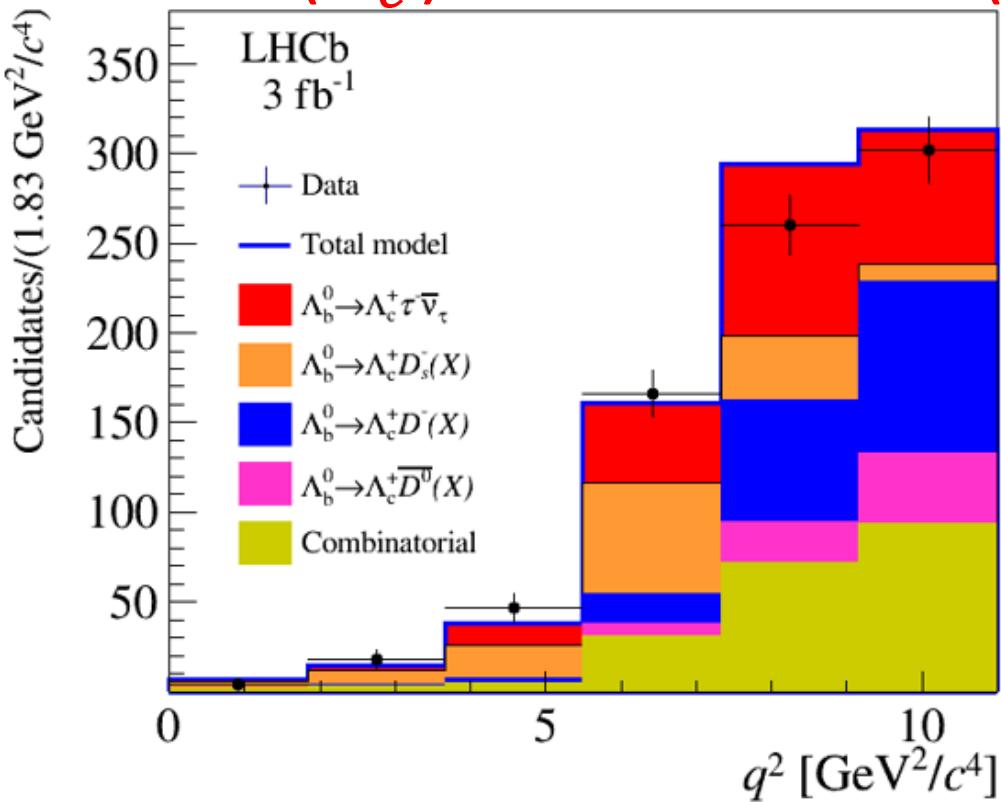
- Data sample with similar selection as that for signal decays
 - No detachment criteria on $3\pi^\pm$ vertex



- $N(B^0 \rightarrow D^{*-} 3\pi^\pm) = 30540 \pm 182$

LHCb measurement of $R(\Lambda_c)$ with hadronic τ decays

$$\mathcal{R}(\Lambda_c^+) = 0.242 \pm 0.026 \text{ (stat)} \pm 0.040 \text{ (syst)} \pm 0.059 \text{ (ext)}$$



(SM expectation= 0.324 ± 0.004)

F. Bernlochner et al., Physical Review D 99 055008 (2019)
with input from W. Detmold, C. Lehner, S. Meinel,
Physical Review D 92 034503 (2015)

LHCb only R(D)-R(D*)

