

# Semileptonic-focused $\Lambda_c$ charmed-baryon studies at LHCb

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Flavor Physics with  $b$ -Baryons and  $B_c$  Mesons:  
Opportunities for Discoveries

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- Published measurements:

- Observation of the decay  $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau \nu$  with  $\tau \rightarrow \pi \pi \pi (\pi) \nu$

[Phys. Rev. Lett. 128 (2022) 191803]

- $d\Gamma/dq^2$  measurement of  $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu \nu$

[Phys. Rev. D 96 (2017) 112005]

- Fragmentation fractions of  $\Lambda_b^0$

[Phys. Rev. D 100 (2019) 031102(R)]

- Ongoing measurements:

- First observation and BR measurement of the  $\Lambda_b^0 \rightarrow \Lambda_c^+(2595,2625) D_s^{(*)}$  decays

- Form factor measurement in  $\Lambda_b^0 \rightarrow \Lambda_c^+(2595,2625) \mu \nu$

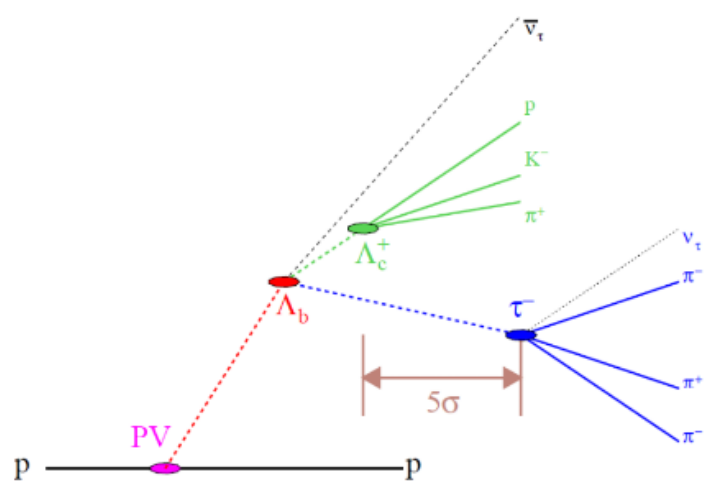
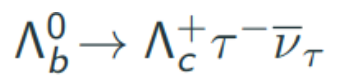
- Determination of  $R(\Lambda_c)$  via  $\tau \rightarrow \mu \nu \nu$

- Angular analysis of  $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu \nu$

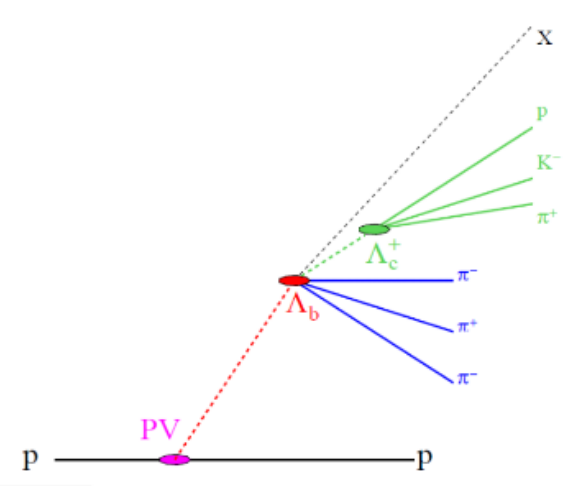
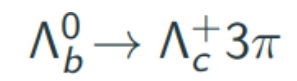
# $R(\Lambda_c)$ measurement

[Phys. Rev. Lett. 128 (2022) 191803]

- First LFU test in a baryonic  $b \rightarrow c\ell\nu$  decay
- Initial state spin 1/2  $\Rightarrow$  could couple to different physics beyond SM
- Three-prong hadronic decays  $\tau \rightarrow \pi\pi\pi(\pi^0)$
- Dataset: run1 LHCb data



$$\mathcal{K}(\Lambda_c^+) = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi)}$$

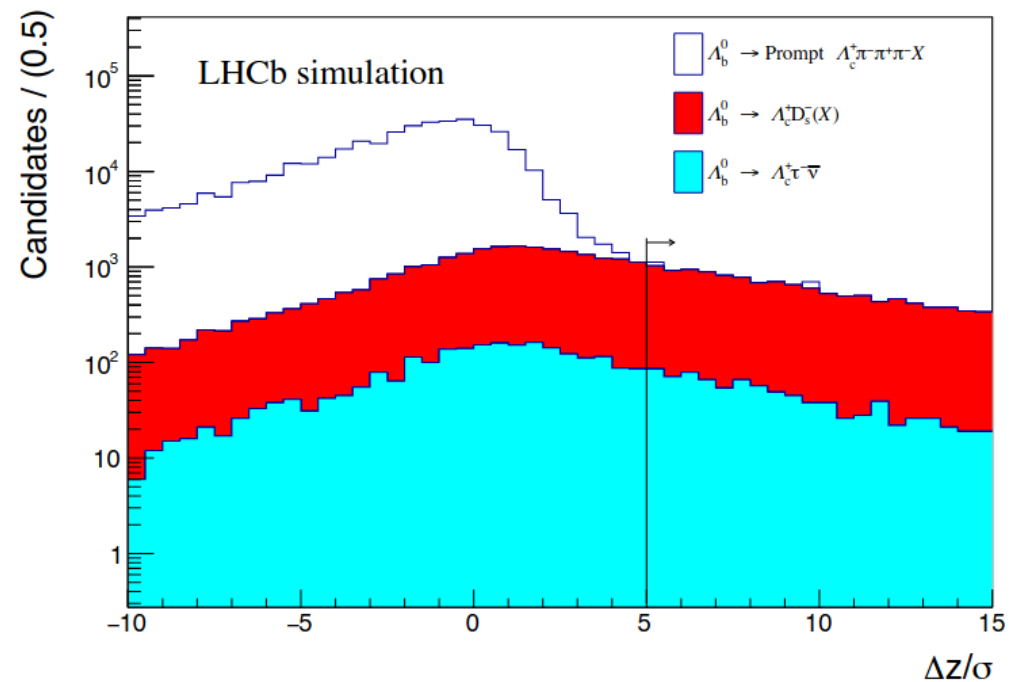


$$R(\Lambda_c^+) = \mathcal{K}(\Lambda_c^+) \left\{ \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu)} \right\} \text{ext. input [PDG 2020]}$$

[Phys. Rev. Lett. 128 (2022) 191803]

- Tight  $\Lambda_c^+$  particle identification selection.
- $\Lambda_c^+$  sideband template used in the signal fit to remove the background under the peak
- Combine with detached  $\pi\pi\pi$  triplet forming  $\tau$  candidates
- Reconstruct decay kinematics
- Prompt background rejection thanks to vertex topology
- $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi\pi\pi X$ 
  - Suppressed by requiring the  $\tau$  vertex to be downstream wrt  $\Lambda_b^0$  vertex along beam direction with a  $5\sigma$  significance

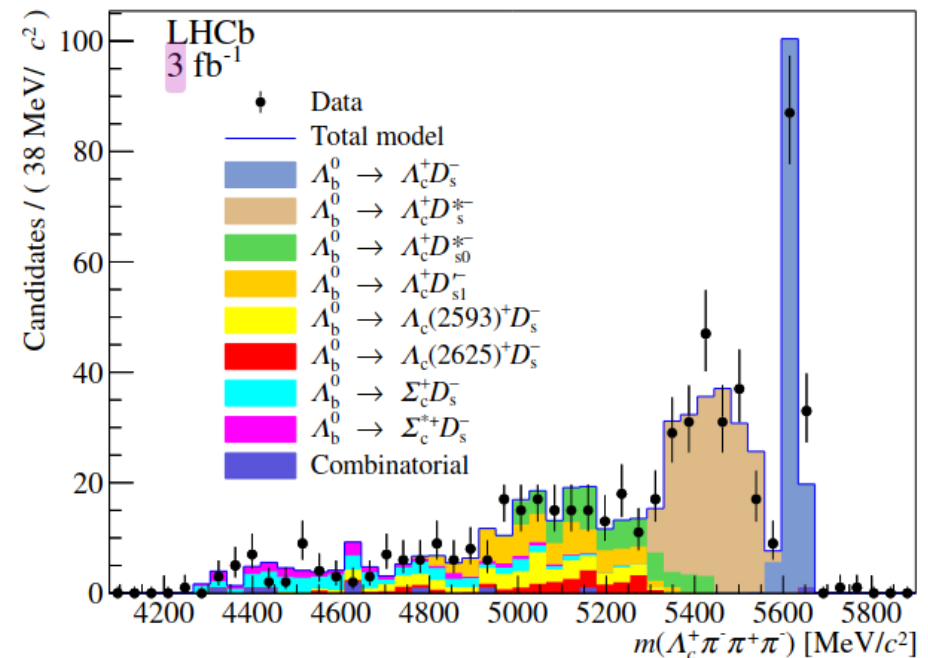
$$\Delta z = z(3\pi) - z(\Lambda_c) > 5 \sigma_{\text{VTX}}$$



[Phys. Rev. Lett. 128 (2022) 191803]

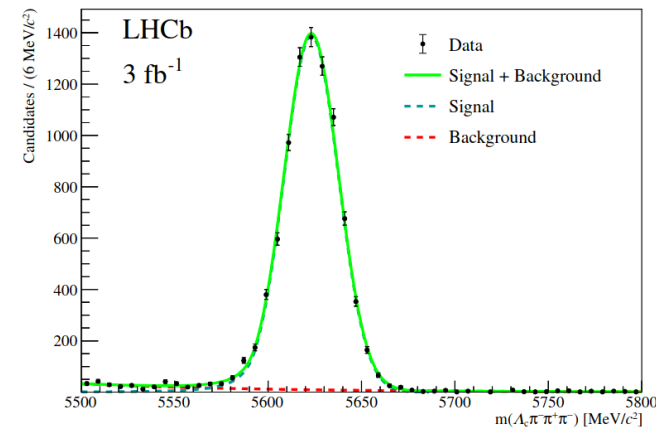
- $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s (\rightarrow \pi\pi\pi X)$ 
  - Suppressed using a BDT:
    - exploit  $\tau$  decay dynamics and taking into account the resonant structure of the  $3\pi$  system
    - the energy carried by neutral particles within the cone around the  $3\pi$  direction
    - kinematic variables from partial reconstruction
- Validated with control samples:  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi\pi\pi$ ,  $\Lambda_b^0 \rightarrow \Lambda_c^+ D^-(X)$ ,  $\Lambda_b^0 \rightarrow \Lambda_c^+ D^0\text{bar}(X)$

- Exclusive  $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s (\rightarrow \pi\pi\pi X)$  control sample to constrain the double charm decays

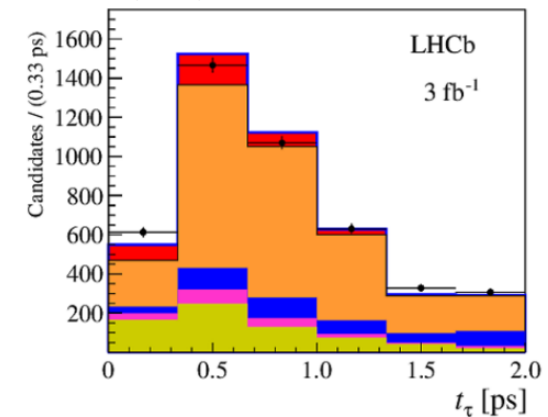
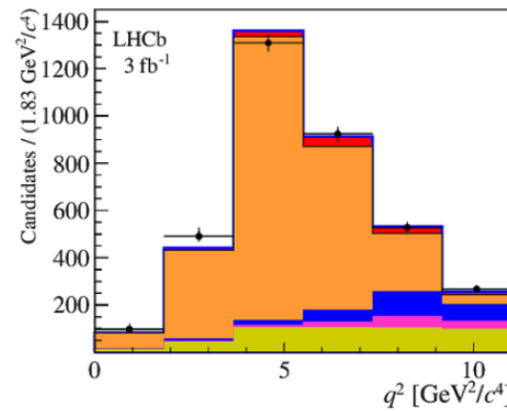


[Phys. Rev. Lett. 128 (2022) 191803]

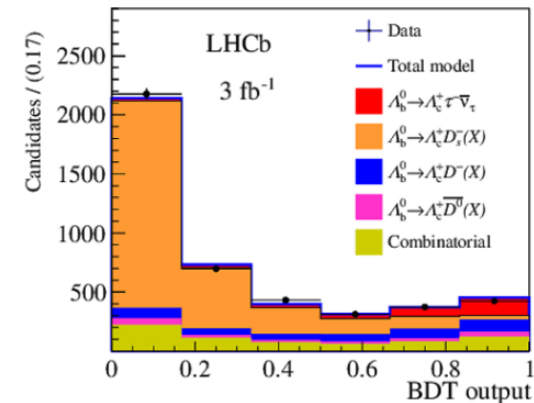
- $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi \pi \pi$  yield extracted from fit to the invariant mass



- Signal yield extracted from fit to
  - $q^2$
  - $\tau$  decay time
  - isolation BDT output



- **First observation of the mode  $\Lambda_b^0 \rightarrow \Lambda_c^+ \tau \nu$  with a  $6\sigma$  significance**



[Phys. Rev. Lett. 128 (2022) 191803]

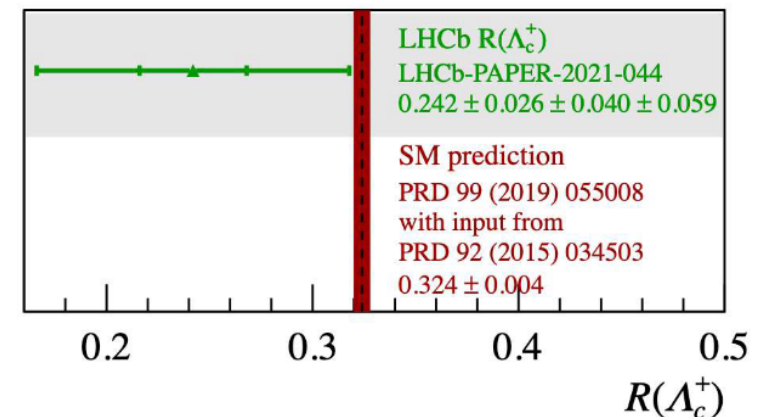
- $\mathcal{K}(\Lambda_c) = 2.46 \pm 0.27(\text{stat}) \pm 0.40(\text{syst})$
- Dominant source of systematic uncertainty is double charm background template shapes

Source	$\delta\mathcal{K}(\Lambda_c^+)/\mathcal{K}(\Lambda_c^+)[\%]$
Simulated sample size	3.8
Fit bias	3.9
Signal modelling	2.0
$\Lambda_b^0 \rightarrow \Lambda_c^{*+}\tau^-\bar{\nu}_\tau$ feeddown	2.5
$D_s^- \rightarrow 3\pi Y$ decay model	2.5
$\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^- X$ , $\Lambda_b^0 \rightarrow \Lambda_c^+ D^- X$ , $\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 X$ background	4.7
Combinatorial background	0.5
Particle identification and trigger corrections	1.5
Isolation BDT classifier and vertex selection requirements	4.5
$D_s^-$ , $D^-$ , $\bar{D}^0$ template shapes	13.0
Efficiency ratio	2.8
Normalisation channel efficiency (modelling of $\Lambda_b^0 \rightarrow \Lambda_c^+ 3\pi$ )	3.0
Total uncertainty	16.5

- $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c \tau^- \bar{\nu}_\tau) = (1.50 \pm 0.16(\text{stat}) \pm 0.25(\text{syst}) \pm 0.23(\text{ext})) \%$

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

- In agreement with SM prediction within  $1\sigma$



# Why $\Lambda_b \rightarrow \Lambda_c(2595, 2625)$

- $\Lambda_c^*$  correspond to  $L=1$  excited  $\Lambda_c$ . They consist of an isospin doublet:
  - $\Lambda_c(2625)$  is a  $J = 3/2$
  - $\Lambda_c(2595)$  is a  $J = 1/2$
- These  $\Lambda_c^*$  resonances decay in  $\Lambda_c \pi^- \pi^+$ 
  - The two charged pions give good vertex reconstruction and clean experimental signature
- These  $\Lambda_c^*$  excited states avoid contamination due higher mass c-baryons
  - reduce the feed-down from higher mass charm baryons
- The widths of these  $\Lambda_c^*$  resonances are narrow:
  - $\Gamma(\Lambda_c(2625)) < 0.97 \text{ MeV}$  (PR D84 012)
  - $\Gamma(\Lambda_c(2595)) = 2.59 \pm 0.30$  (Chin. Phys. C, 40, 100001 (2016))
- Muonic  $R(\Lambda_c^*)$  feasibility studies highlight two dominant systematic uncertainties: double-charm backgrounds and form-factor knowledge.

# Why $\Lambda_b^0 \rightarrow \Lambda_c^* D_s^{(*)}$ ?

- The branching ratio of such decays has never been measured before.
- The decays  $\Lambda_b^0 \rightarrow \Lambda_c^* D_s^{(*)}$  are of interest because they provide an opportunity to investigate the nature of the  $\Lambda_c(2595)$  and  $\Lambda_c(2625)$  states  
[10.1140/epjc/s10052-017-4602-6]
- LFU tests with semileptonic  $\Lambda_b \rightarrow \Lambda_c^*$  decays are important in order to corroborate the present anomalies on decays with charmed mesons via the measurement of

$$R(\Lambda_c^*) = B(\Lambda_b^0 \rightarrow \Lambda_c^{*+} \tau^- \bar{\nu}_\tau) / B(\Lambda_b^0 \rightarrow \Lambda_c^{*+} \mu^- \bar{\nu}_\mu)$$

- To understand the  $\Lambda_b \rightarrow \Lambda_c^* \tau \bar{\nu}_\tau$ , it is important to study its dominant background  $\Lambda_b^0 \rightarrow \Lambda_c^* D_s^{(*)}$ , where the  $D_s$  decays semileptonically.
- These decays exhibit kinematical similarities to the decay  $\tau \rightarrow \mu \nu \bar{\nu}$ .

# Observation of the $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^*$ decays

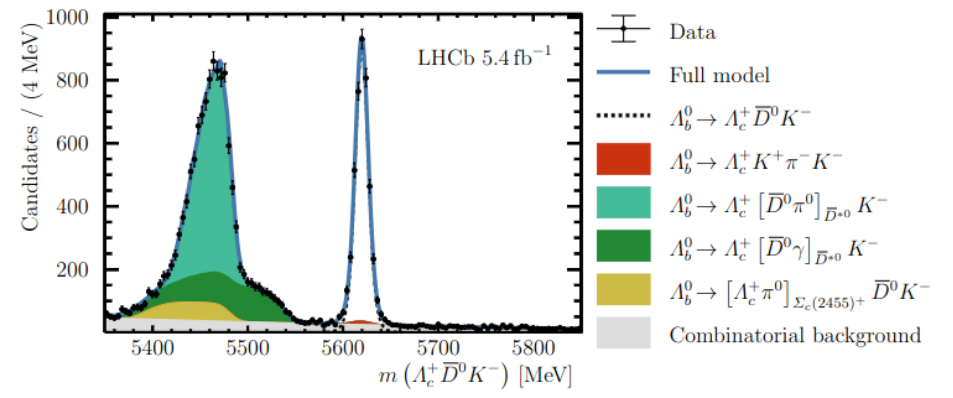
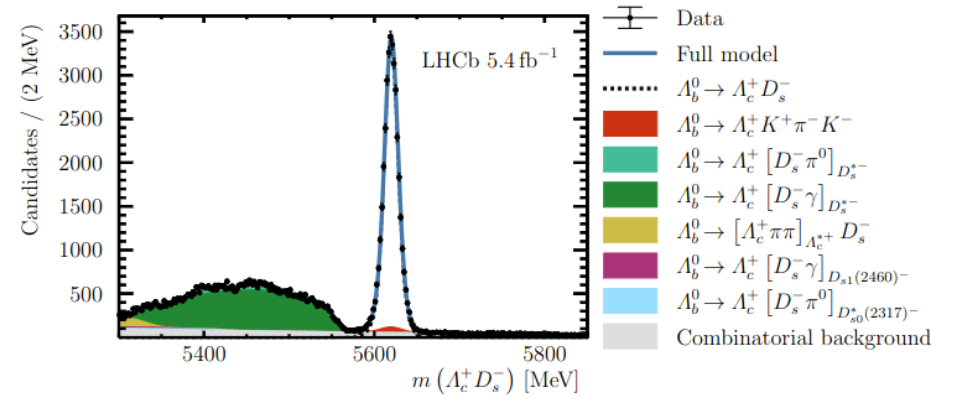
[10.1140/epjc/s10052-024-12752-3]

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)} = 0.1908_{-0.0034-0.0018}^{+0.0036+0.0016} \pm 0.0038,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \bar{D}^{*0} K^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)} = 0.589_{-0.017-0.018}^{+0.018+0.017} \pm 0.012,$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^{*-})}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)} = 1.668 \pm 0.022_{-0.055}^{+0.061},$$

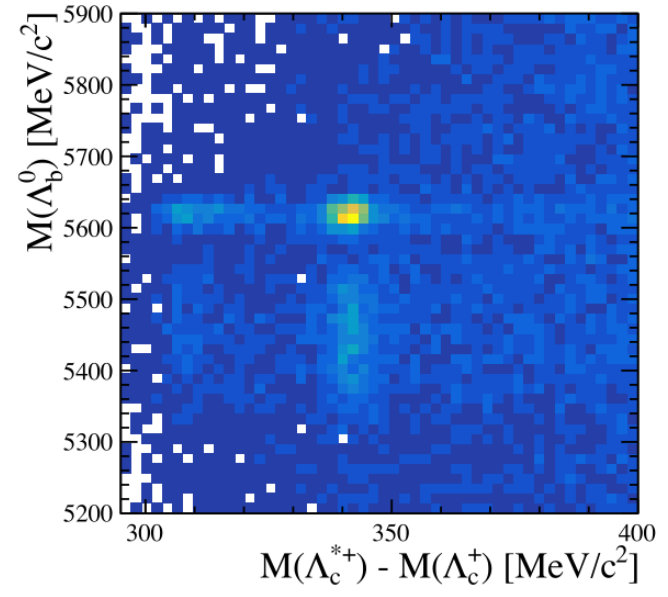
Source/relative to	$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^{*-})}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)}$ [%]
Fit model	+3.6 -3.3
Weighting	0.0
Multiple candidates	0.1
Size of the simulated samples	0.2
Size of the generated samples	0.6
Total	+3.7 -3.3
Statistical	1.3



# Observation of the $\Lambda_b^0 \rightarrow \Lambda_c^* D_s^{(*)}$ decays

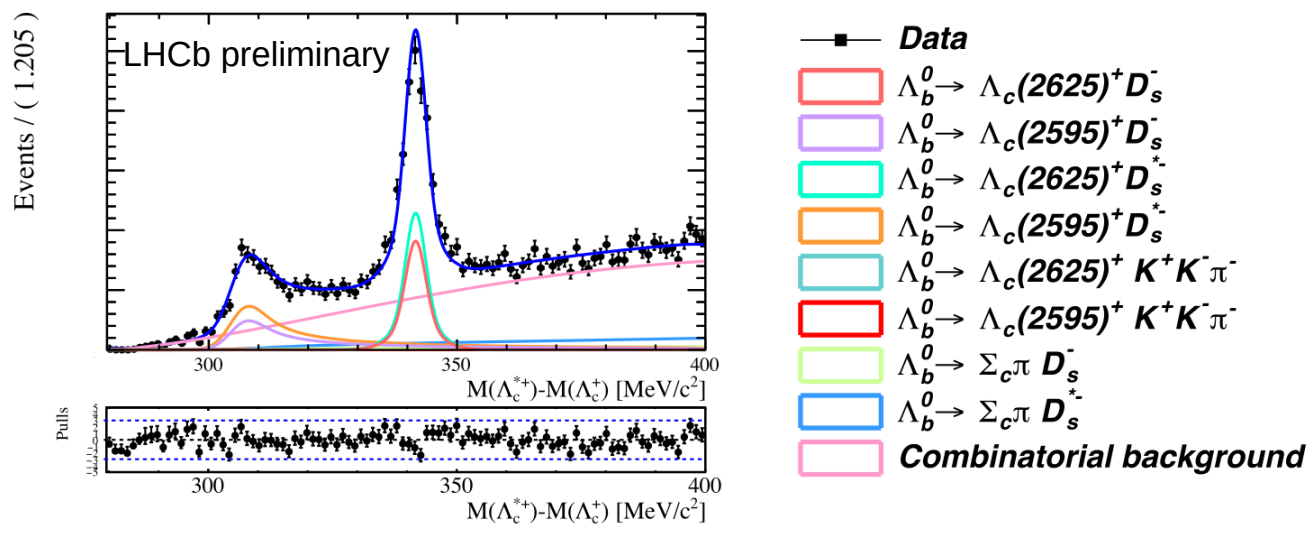
$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow [\Lambda_c(2625, 2595)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-] D_s^-)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)} = \frac{n_{sig}(\Lambda_b^0 \rightarrow \Lambda_c(2625, 2595)^+ D_s^-)}{n_{sig}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)} \cdot \frac{\epsilon(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^-)}{\epsilon(\Lambda_b^0 \rightarrow \Lambda_c(2625, 2595)^+ D_s^-)}$$

$$\frac{\mathcal{B}(\Lambda_b^0 \rightarrow [\Lambda_c(2625, 2595)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-] D_s^{*-})}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^{*-})} = \frac{n_{sig}(\Lambda_b^0 \rightarrow \Lambda_c(2625, 2595)^+ D_s^{*-})}{n_{sig}(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^{*-})} \cdot \frac{\epsilon(\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^{*-})}{\epsilon(\Lambda_b^0 \rightarrow \Lambda_c(2625, 2595)^+ D_s^{*-})}$$

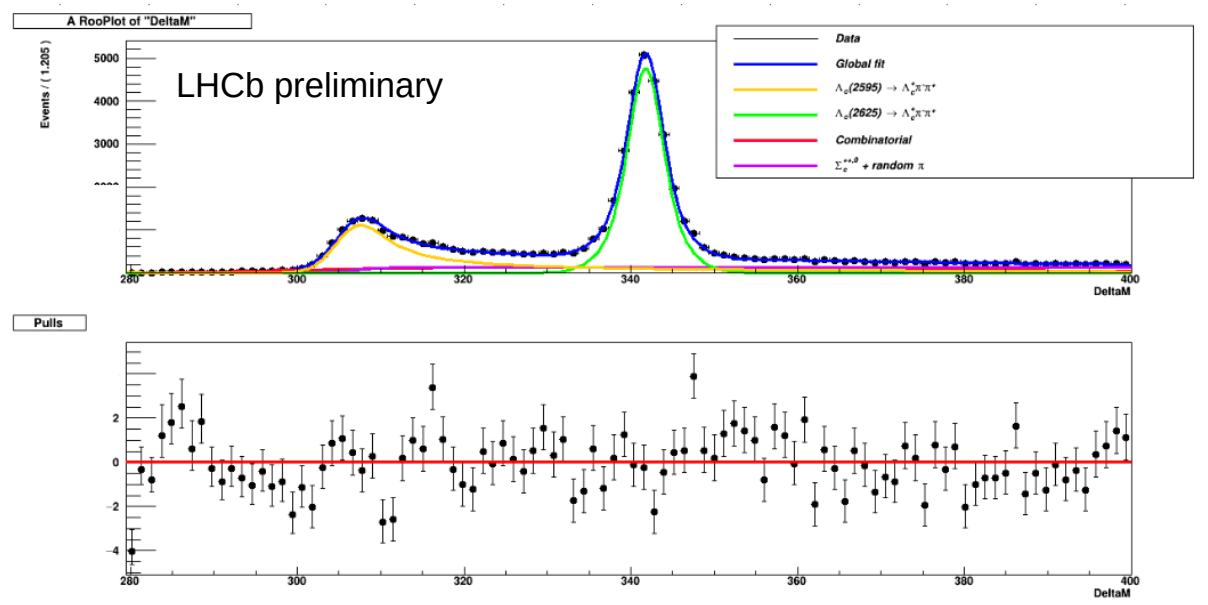
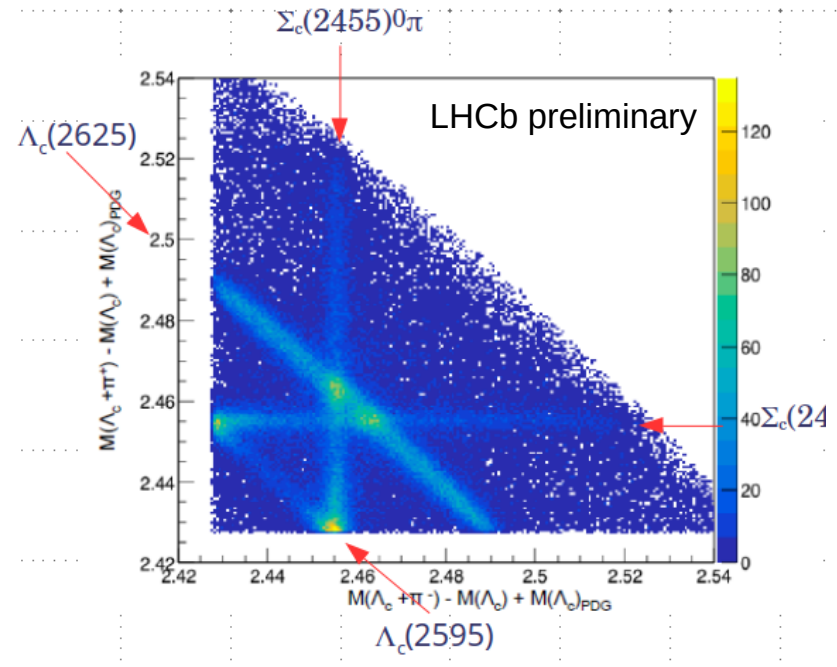


$$\Delta M = M(\Lambda_c^{*+}) - M(\Lambda_c^+)$$

$$M_{inv}(\Lambda_b^0) = M(\Lambda_b^0) - M(\Lambda_c^+) - M(D_s^-) + M(\Lambda_c^+)_{PDG} + M(D_s^-)_{PDG}$$



- Goal of the analysis: constrain short-distance effects and long-distance hadronic effects



[Phys. Rev. D 99, 055008]

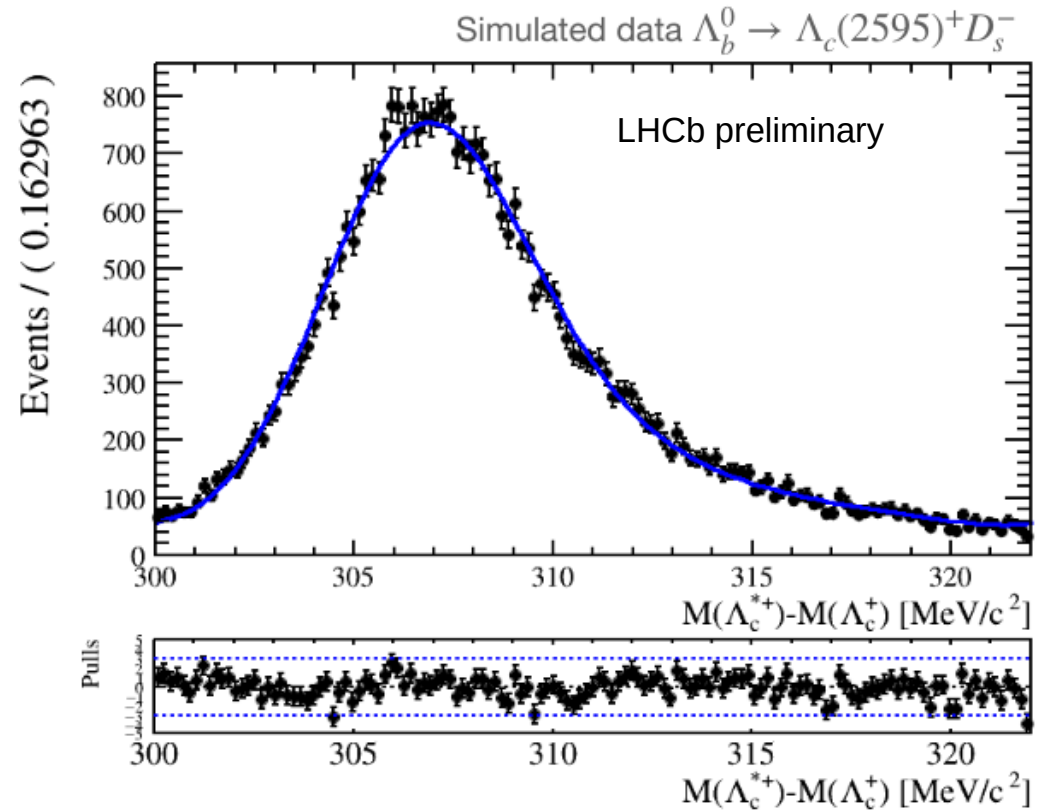
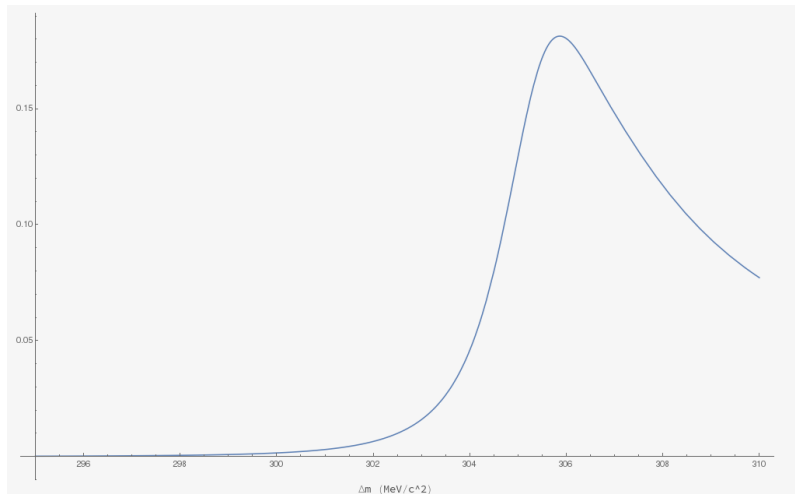
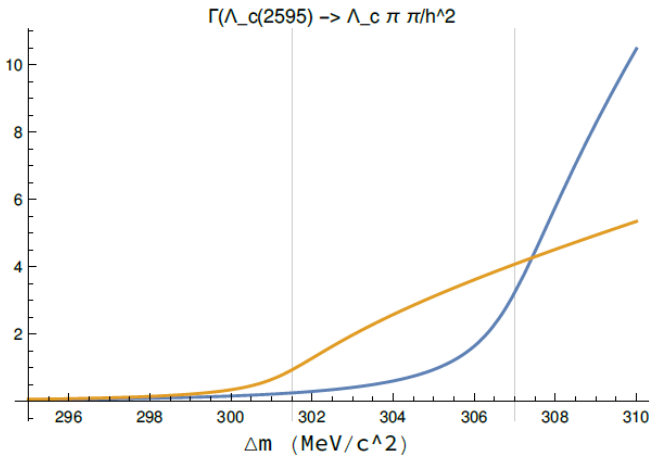
- Extract FF from  $(q^2 - \cos\theta_\mu)$  distributions of  $\Lambda_b \rightarrow \Lambda_c^* \mu \nu$  and
- New fit models??

$$\frac{BR(\Lambda_b \rightarrow \Lambda_c^+(2595)\mu\nu)}{BR(\Lambda_b \rightarrow \Lambda_c^+(2625)\mu\nu)}$$

# $\Lambda_c(2595)$ line shape

- Phenomenological Model implemented: Blechman et al. [[10.1103/PhysRevD.67.074033](https://arxiv.org/abs/10.1103/PhysRevD.67.074033)]
- The state is described by a non relativistic Breit–Wigner function:

$$\frac{dN}{d\Delta M} \propto \frac{\Gamma(\Lambda_c^+ \pi^+ \pi^-)}{(\Delta M - \Delta M_{\Lambda_c(2595)^+})^2 + (\Gamma(\Lambda_c^+ \pi^+ \pi^-) + \Gamma(\Lambda_c^+ \pi^0 \pi^0))^2 / 4}$$



- New models?

# Angular analysis of $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu \nu$

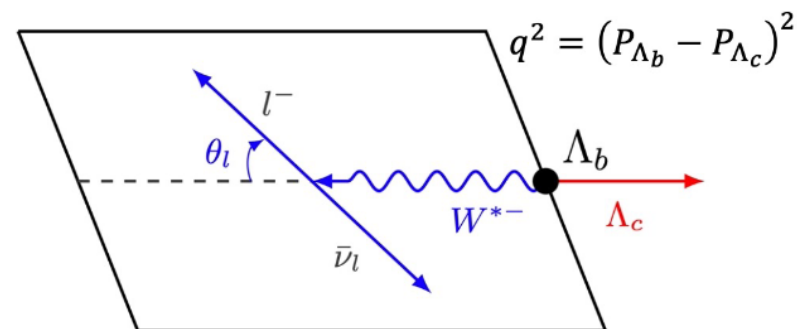
- Goal of the analysis: Constrain the short distance effects (Wilson coefficients (WCs)) and long distance hadronic effects (form factors)

## • Important input

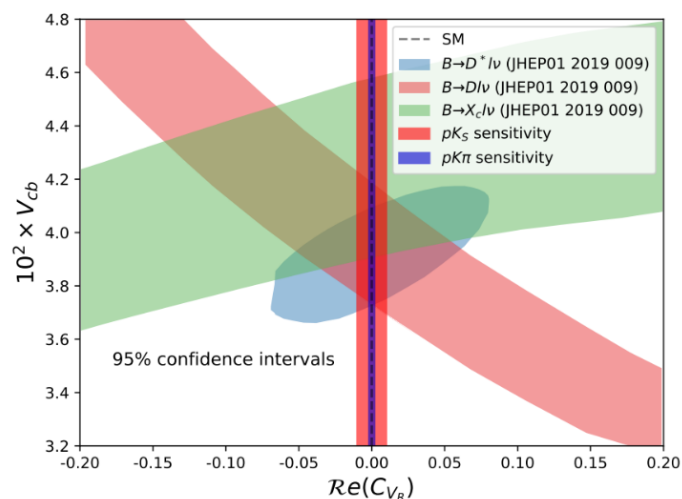
- to both experimental and SM prediction of  $R(\Lambda_c)$
- to constraining New Physics effects in light leptons
- input to  $R(D) - R(D^*)$  LFU tension

• Exclusive  $|V_{cb}|$

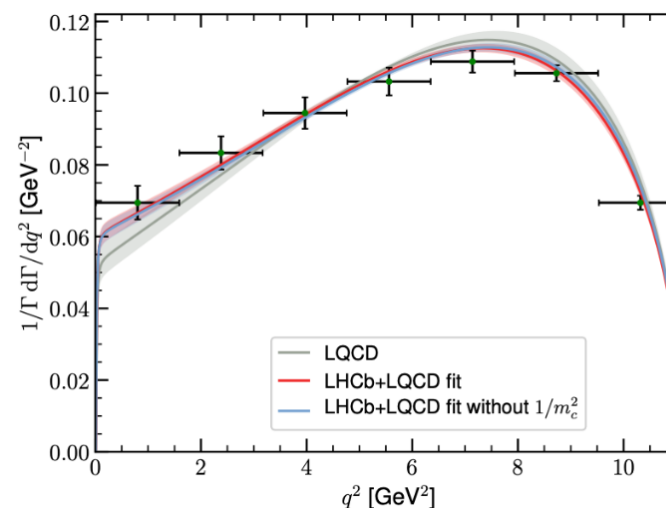
$$\frac{R(\Lambda_c)}{R^{SM}(\Lambda_c)} \cong 0.262 \frac{R(D)}{R^{SM}(D)} + 0.738 \frac{R(D^*)}{R^{SM}(D^*)}$$



[Phys. Rev. D 99,075006(2019)]



[JHEP 12 (2019) 148]



[Phys. Rev. D 99, 055008]

- Extract FF and WCs with normalised phase space ( $q^2 - \cos\theta_\mu$ ) distributions of  $\Lambda_b \rightarrow \Lambda_c \mu \nu$ .

- LHCb has a unique capability for baryonic decays
- First LFU tests in baryonic semileptonic decays are already available
- Several ongoing analyses will improve our understanding of:
  - excited charm baryons
  - form factors
  - double-charm backgrounds
  - LFU tests with  $\Lambda_b$  decays
- Many opportunities ahead, but also many things to do, limited person-power, and so long analyses timescales... stay tuned!

*Thank you for your attention!*