RECENT RESULTS FROM LHCB ON CHARGED-CURRENT DECAYS

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ON BEHALF OF THE LHCB COLLABORATION

RENCONTRES DU VIETNAM, AUGUST 18, 2025

CHARGED-CURRENT B-HADRON DECAYS AT LHCB

- **Charged current (CC) decays** provide direct insight into the **flavour structure** of **quarks** and **leptons**.

- **LHCb's large, diverse b-hadron production**, i.e. B, B_s, B_c and Λ_b, makes it **ideal for studying CC decays of b-hadrons**.

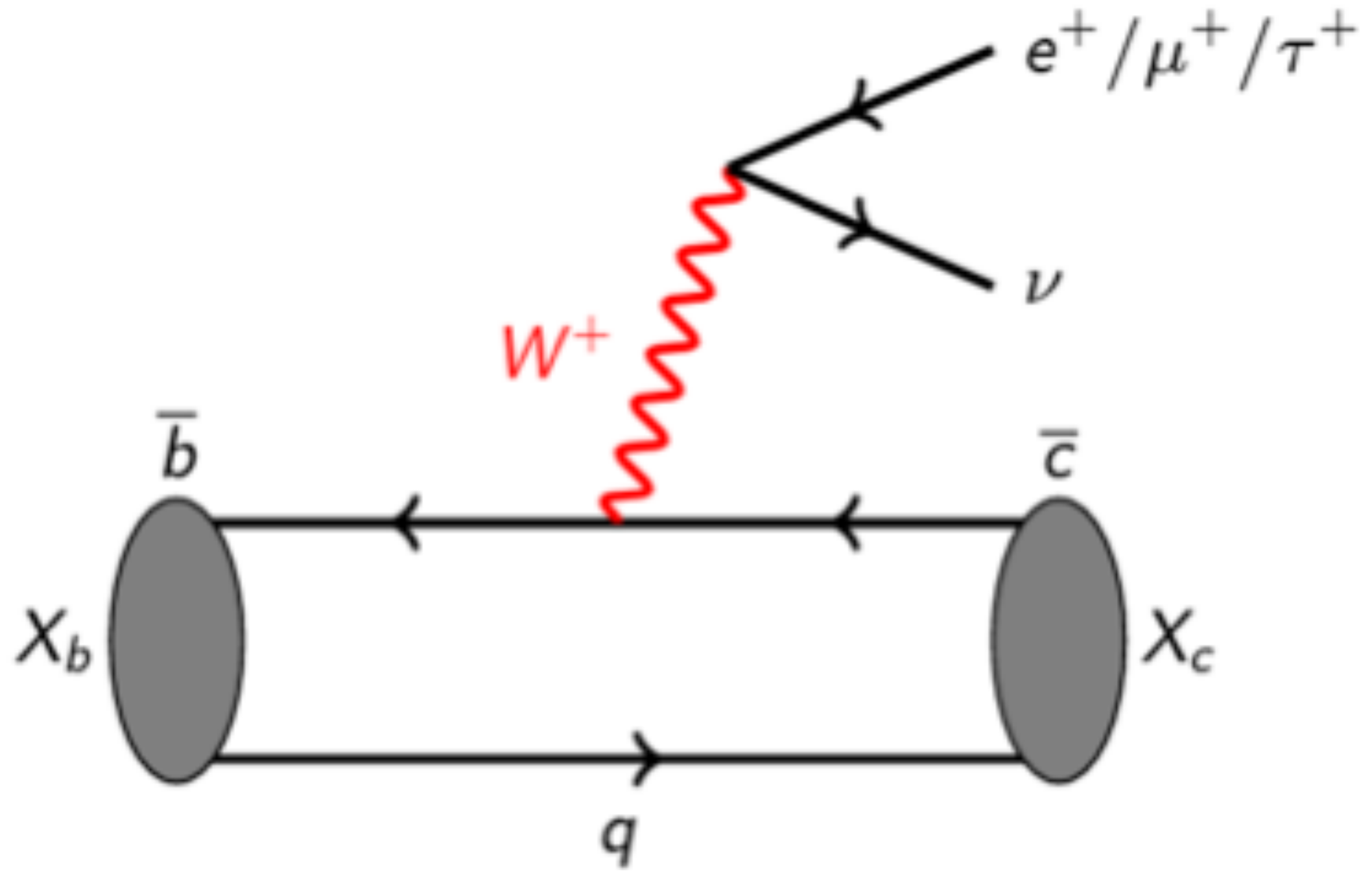
- **LHCb measurements** with CC b-hadron decays:

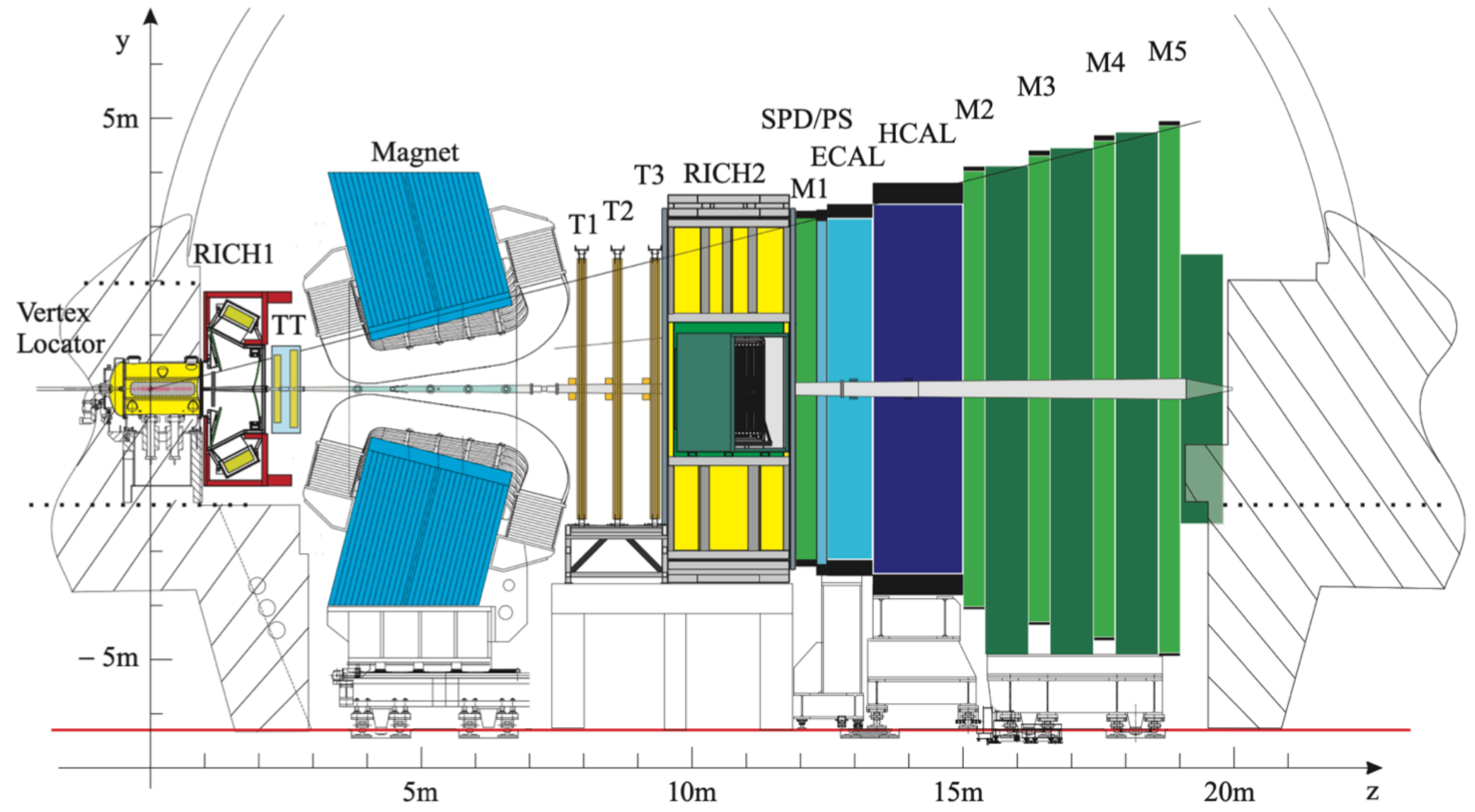
  ★ Testing **lepton flavour universality** (LFU).

  ★ Searching for signs of **new physics** (NP).

  ★ Precision determination of **CKM elements** $|V_{cb}|$ and $|V_{ub}|$.

➡ Latest results focus on **LFU** and will be the **highlight of this talk**.





OUTLINE OF TODAY'S TALK

- Introduction to **LFU tests**
  - Testing LFU @LHCb with **branching fraction ratios**.
    - Recent $R(D)$, $R(D^*)$ measurements
    - D^* longitudinal polarisation fraction
    - Study of $B \to D^{**0}\tau\nu_\nu$ decays
    - New $\Lambda \to p\mu^-\bar{\nu}_\mu$ result
  - Conclusion and outlook

LEPTON FLAVOUR UNIVERSALITY TESTS

- **Lepton flavour universality (LFU):** electroweak interaction couples equally to all lepton flavours.

  Key axiom of the SM → **violation** would be a **clear sign of NP**.

Difference between e, μ and τ driven only by mass

- **Experimentally tested in:**

  (1) Direct Z and W decays:

  [PHYS. REPT. 427 (2006)]

  $$\frac{\Gamma_{\mu\mu}}{\Gamma_{ee}} = \frac{BR(Z \to \mu^+\mu^-)}{BR(Z \to e^+e^-)} = 1.0009 \pm 0.0028$$

  [NATURE PHYSICS 17, 813 (2021)]

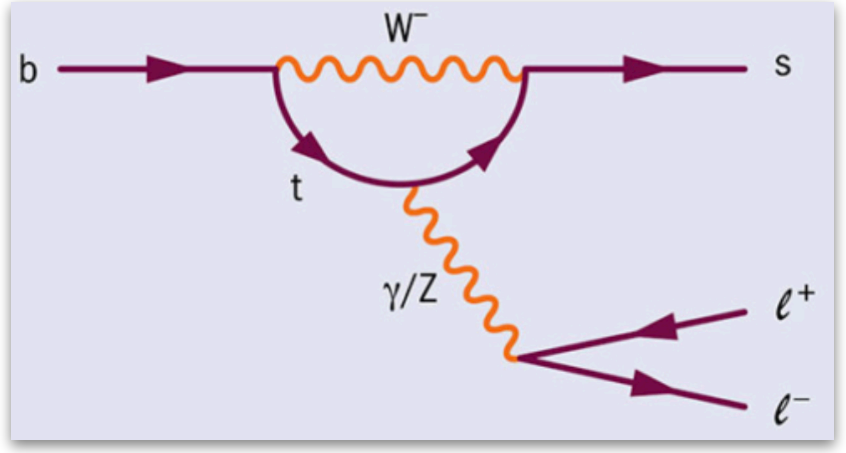
  $$\frac{\Gamma_{\tau\nu}}{\Gamma_{\mu\nu}} = \frac{BR(W \to \tau\nu_\tau)}{BR(W \to \mu\nu_\mu)} = 0.992 \pm 0.013$$

  → Overall, results are consistent with SM.

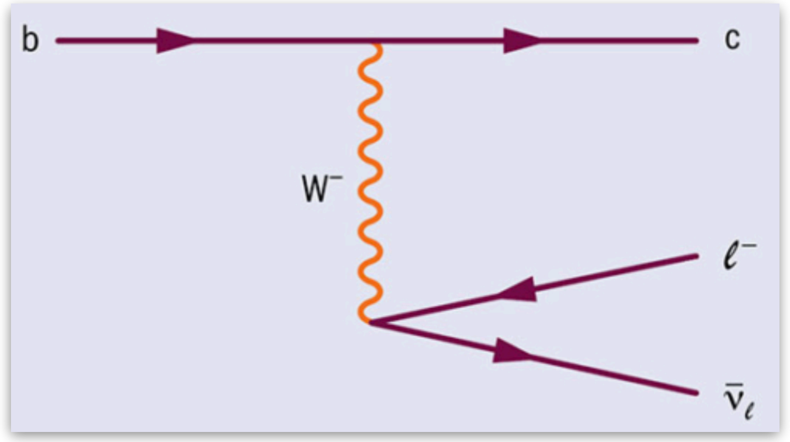
  (2) Weakly decaying hadrons:

  → Conclusion less clear.

Flavour changing **neutral currents** (FC**NC**)

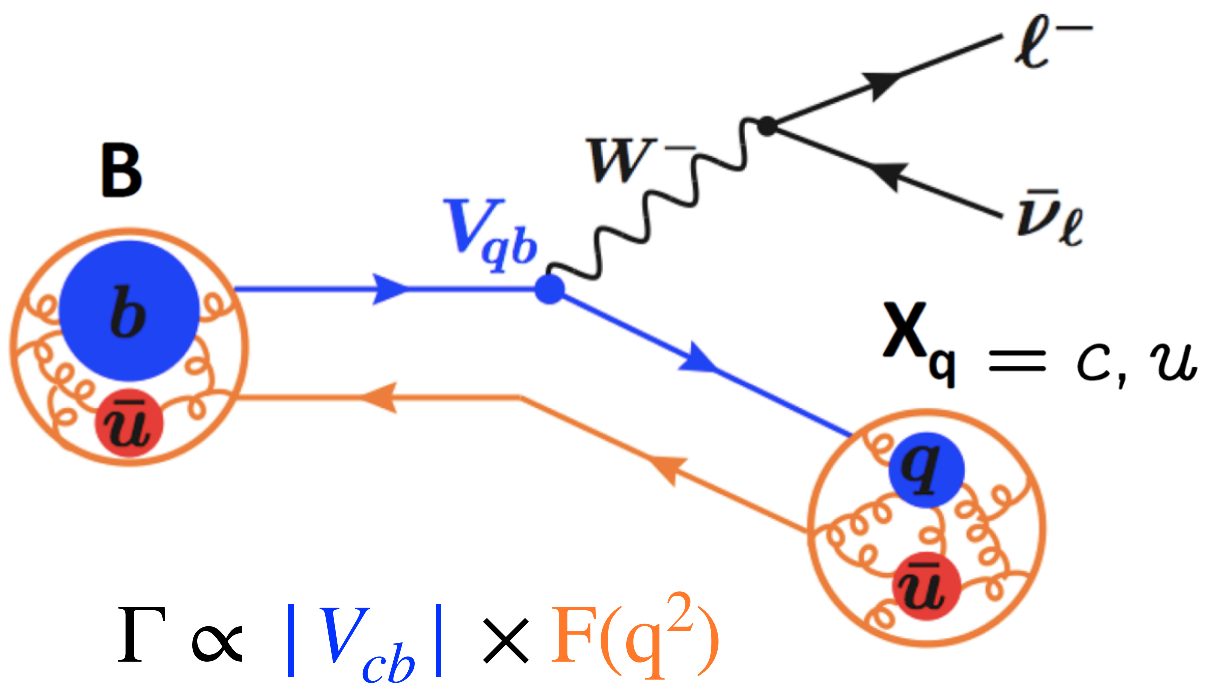


Flavour changing **charged currents** (FC**CC**)



→ **Excess of tauonic decay modes in CC decays (NP?).**

Testing LFU with BR ratios of SL $b \to c l \nu$ decays:



$$\Gamma \propto |V_{cb}| \times F(q^2)$$

$$R(X_c) = \frac{BR(X_b \to X_c \tau^- \bar{\nu}_\tau)}{BR(X_b \to X_c \mu^- \bar{\nu}_\mu)}$$

CKM and **hadronic form factor** uncertainties largely cancel out

$$X_b = B^0, B^+, B^0_s, B^+_c, \Lambda^0_b$$

$$X_c = D^0, D^+, D^+_s, D^{*+/0}, D^{**+/0}, \Lambda^+_c, \Lambda^{*+}_c, J/\psi$$

★ In this talk

SUMMARY OF LFU PAPERS FROM LHCB

Muonic τ^- decays

Run 1 (2015) [PRL 115, 111803]

$R(D^{*+}) = 0.336 \pm 0.027(\text{stat}) \pm 0.030(\text{syst})$

Run 1 (2023) [PRL 131, 111802]

$R(D^{*}) = 0.281 \pm 0.018(\text{stat}) \pm 0.024(\text{syst})$

$R(D^{0}) = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{syst})$

★ **Run 2 (2025)** [PRL 134, 061801]

$R(D^{*+}) = 0.402 \pm 0.081(\text{stat}) \pm 0.085(\text{syst})$

$R(D^{+}) = 0.249 \pm 0.043(\text{stat}) \pm 0.047(\text{syst})$

Run 1 (2018) [PRL 120, 121801]

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

Hadronic τ^- decays

Run 1 (2018) [PRL 120, 171802]

$R(D^{*+}) = 0.291 \pm 0.019(\text{stat}) \pm 0.026(\text{syst}) \pm 0.013(\text{ext})$

★ **Part of Run 2 (2023)** [PRL 108, 012018]

$R(D^{*+}) = 0.260 \pm 0.015(\text{stat}) \pm 0.016(\text{syst}) \pm 0.012(\text{ext})$

Run 1 (2022) [PRL 128, 191803]

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

★ **Run 1 & part of Run 2 (2024)** [PRD 110, 092007]

$F_L^{D^*} = 0.41 \pm 0.06(\text{stat}) \pm 0.03(\text{syst})$

★ **Run 1 & 2 (2025)** [PRL 135, 021802]

$R(D_{1,2}^{**0}) = 0.13 \pm 0.03(\text{stat}) \pm 0.01(\text{syst}) \pm 0.02(\text{ext})$

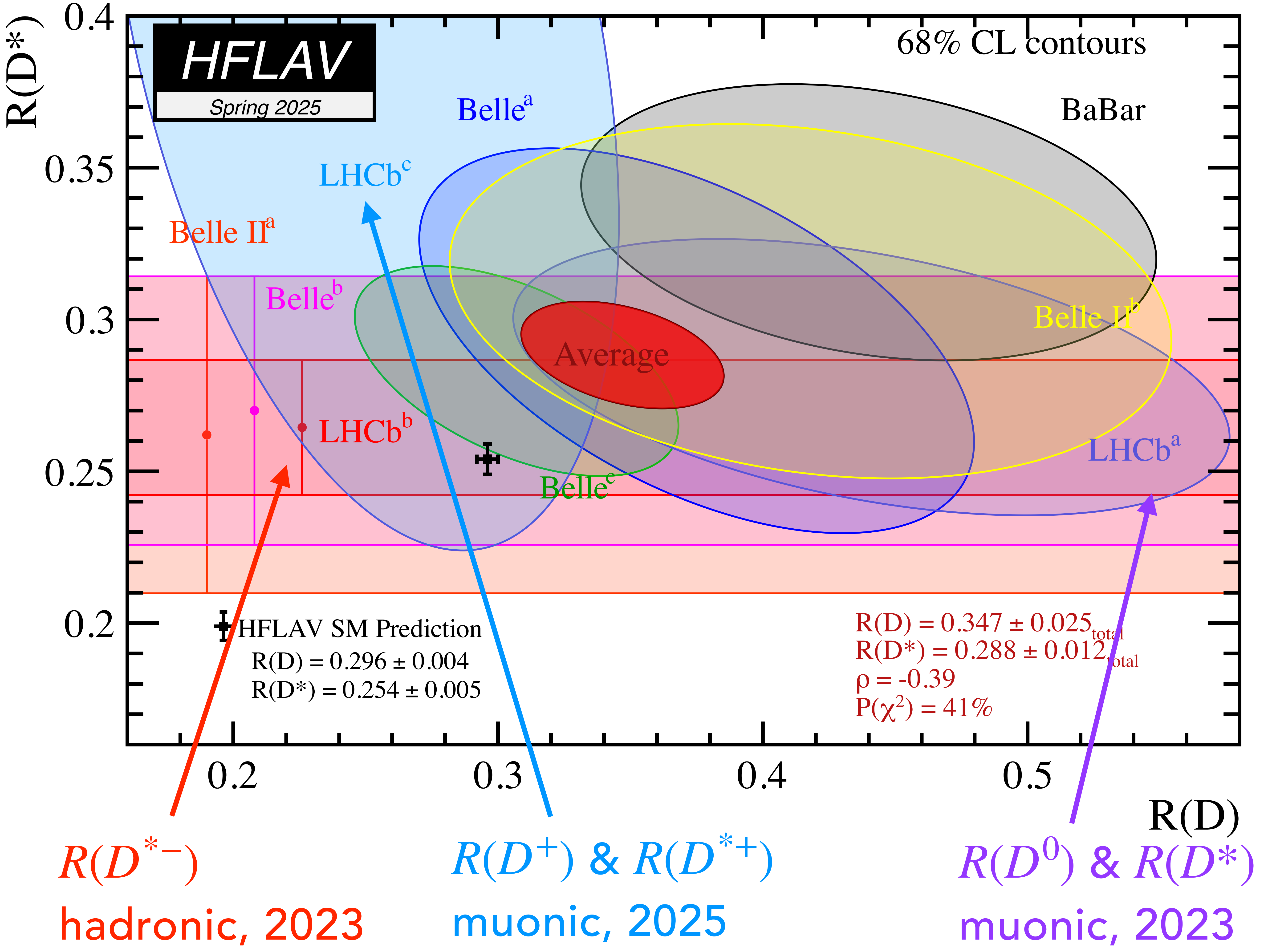
$R(D)$, $R(D^*)$

CURRENT STATUS ON $R(D)$, $R(D^*)$

- **HFLAV average of $R(D^{(*)})$** is **3.8σ from SM**.

  → Suggesting an **excess of semitauonic decays**.

- **Possible NP explanations:**
  - Models leading to **enhancement of semitauonic decays**.
  - **Two-Higgs doublet** [1], **Leptoquarks** [2] & **non-universal left-right** [3] models.



[1] Rev. Mod. Phys. 94, 015003 (2022).

[2] Phys. Rev. D 94, 034001 (2016).

[3] Phys. Rev. D 87, 014014 (2013).

$R(D^{+})$ & $R(D^{*+})$ MUONIC, 2025

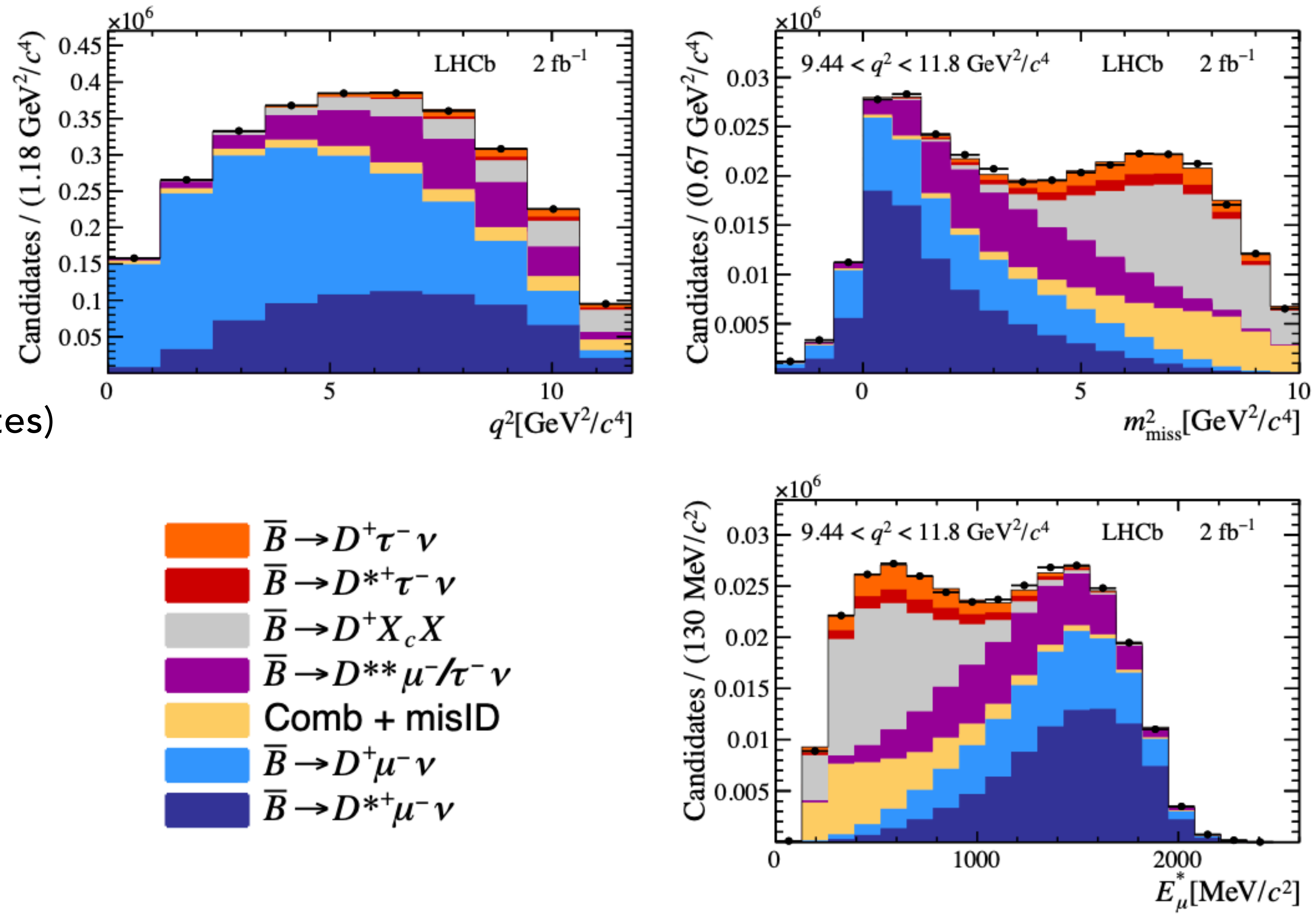
- **Run 2 data (2015-2016)** with $\mathscr{L}_{\text{int}} = 2\ \text{fb}^{-1}$.
- **First simultaneous $R(D^{+})$ & $R(D^{*+})$ @LHCb:**

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

$D^{*+} \to D^+\pi^0$, $D^+ \to K^-\pi^+\pi^+$ (π^0 → not reconstructed)

$\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ (SL muonic and tauonic modes → same visible final states)

- **3D template fit:**
  - ❖ $q^2 = (p_B - p_{D^{(*)}})^2$
  - ❖ $E^*_\mu \to E_\mu$ in the B rest frame
  - ❖ $m^2_{\text{miss}} = (p_B - p_{D^{(*)}} - p_\mu)^2$
  - Templates modelled with **simulation** and **data**.
  - ❖ **Simultaneous fit to four regions** based on **track isolation BDT**.
    - ✳ **Signal:** no tracks in the vicinity of signal.
    - ✳ **One-pion:** one additional pion → targeting $B \to D^{**}\mu/\tau\nu$.
    - ✳ **Two-pion:** two additional pions → targeting $B \to D^{**}\mu/\tau\nu$.
    - ✳ **One-kaon:** one additional kaon → targeting $B \to D^{+}X_cX$.
  - ➡ **propagates corrections** to the signal region.



$R(D^{+}) = 0.249 \pm 0.043(\text{stat}) \pm 0.047(\text{syst})$

$R(D^{*+}) = 0.402 \pm 0.081(\text{stat}) \pm 0.085(\text{syst})$

$\rho = -0.39$

Results agree with SM and global average.

$R(D^{*-})$ HADRONIC, 2023

- **Run 2 data (2015-2016)** with $\mathscr{L}_{\text{int}} = 2\ \text{fb}^{-1}$.

- $R(D^{*-})$ **with hadronic** $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\nu$ **decays**:

  → SL muonic and tauonic modes have different visible final states!

  → normalising to $B^0 \to D^{*-}3\pi$ to reduce uncertainties!

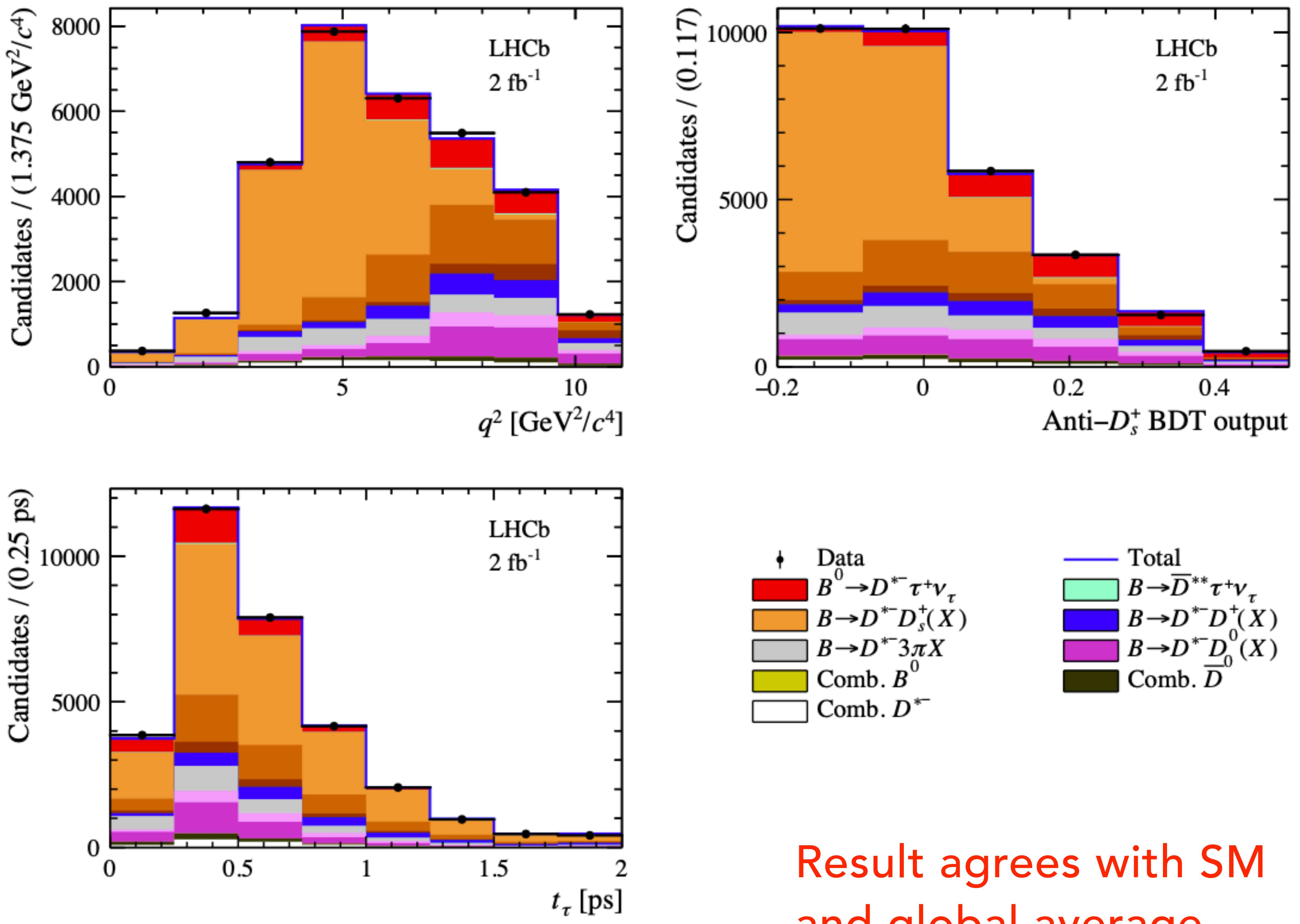
$$R(D^{*-}) = \frac{BR(B^0 \to D^{*-}\tau^+\nu_\tau)}{BR(B^0 \to D^{*-}3\pi)} \times \frac{BR(B^0 \to D^{*-}3\pi)}{BR(B^0 \to D^{*-}\mu^+\nu_\mu)},$$

$D^{*-} \to \bar{D}^0\pi^-$, $\bar{D}^0 \to K^+\pi^-$

$BR(B^0 \to D^{*-}3\pi)$ and $BR(B^0 \to D^{*-}\mu^+\nu_\mu)$ → external inputs.

- **3D template fit:**
  - ❖ $q^2 = (p_{B^0} - p_{D^{*-}})^2$
  - ❖ t_τ : τ decay time
  - ❖ Anti-D_s^+ BDT output

- Templates modelled with simulation and data.
- Control studies to suppress, model and correct backgrounds.



Result agrees with SM and global average.

$$R(D^{*-}) = 0.260 \pm 0.015(\text{stat}) \pm 0.016(\text{syst}) \pm 0.012(\text{ext})$$

Most precise R(D*) to date.

$$F_L^{D^*}$$

D^* LONGITUDINAL POLARISATION FRACTION, 2024

- **Run 1 & Run 2 (2015-2016) data** with $\mathscr{L}_{\text{int}} = 5\ \text{fb}^{-1}$.

- **The D^* longitudinal polarisation fraction, $F_L^{D^*}$:**
  - ★ Additional sensitivity to possible **NP scenarios**.

- **Measured with $B^0 \to D^{*-}\tau^+\nu_\tau$ with hadronic τ decay:**

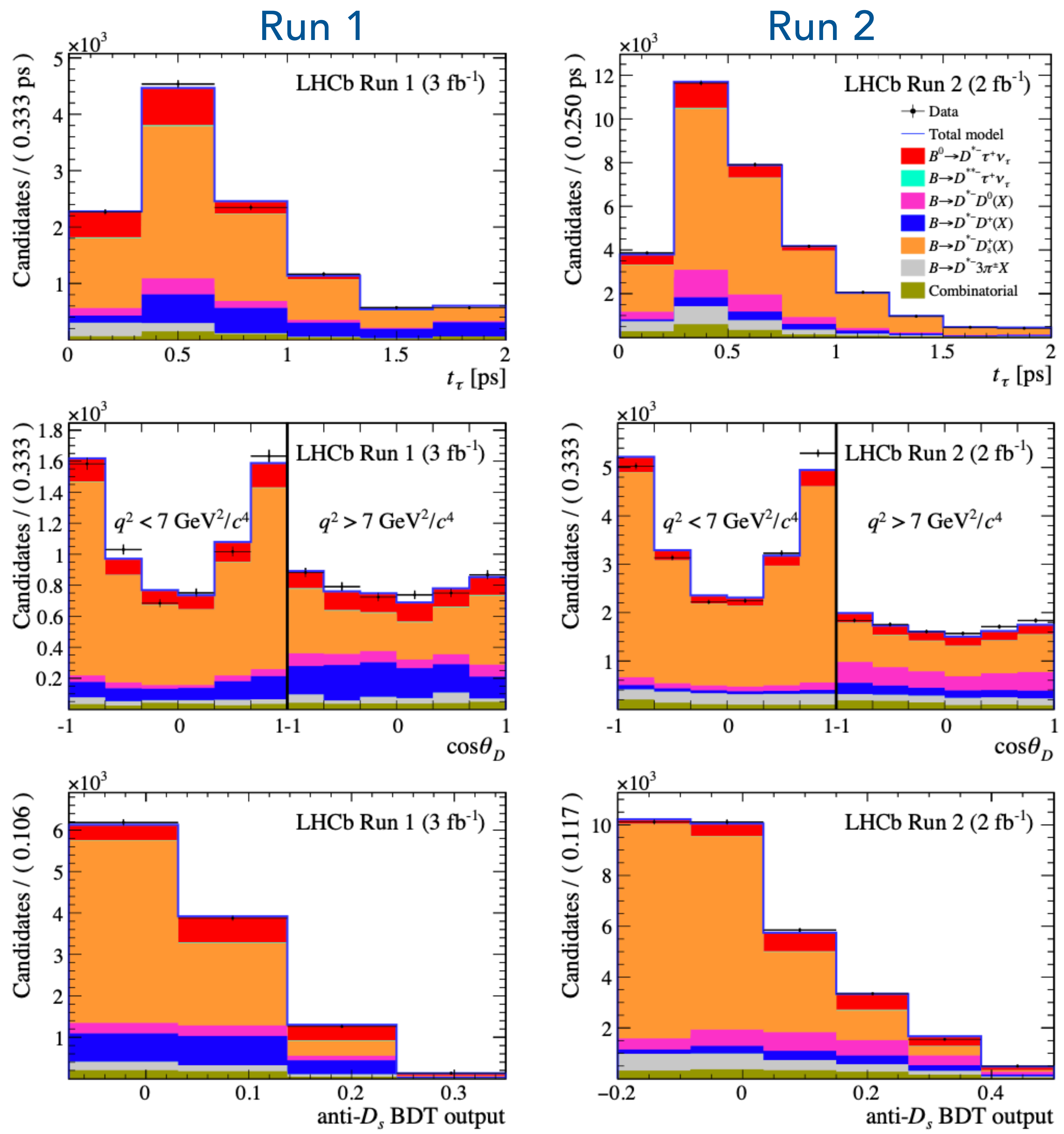
$$F_L^{D^*}(q^2) = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)},$$

θ_D : angle between $\bar{D}^0$ direction vs. direction opposite to B^0 in the D^* rest frame.

a_{θ_D} and c_{θ_D} inferred from the $D^{*-} \to \bar{D}^0\pi^-$ differential decay rate:

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$$

- **4D template fit to q^2, $\cos(\theta_D)$, Anti-D_s^+ BDT output** and t_τ.
  - ➡ a_{θ_D} and c_{θ_D} determined from polarised and unpolarised signal fit templates.



$$F_L^{D^*} = 0.41 \pm 0.06(\text{stat}) \pm 0.03(\text{syst})$$

→ Consistent with SM prediction and previous Belle measurement [arXiv:1903.03102].

$$B^- \to D^{**0}\tau^-\bar{\nu}_\tau$$

STUDYING $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ DECAYS

- **Full Run 1 & 2 data with $\mathscr{L}_{\text{int}} = 9\ \text{fb}^{-1}$.**
- **Motivation:** large systematic uncertainty in $R(D^{(*)})$ from limited knowledge on $B \to D^{**}\tau^-\bar{\nu}_\tau$ feed-down.
- **Reconstruction & Normalisation:**
  - ✴ Signal $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ with hadronic $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\nu$.
  - ✴ Normalised to $B^- \to D_{1,2}^{**0}D_s^{(*)-}$ with $D_s^- \to \pi^-\pi^+\pi^-$.
  - ✴ Both: $D_{1,2}^{**0} \to D^{*+}\pi^-$, $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$

→ Same visible final state + vertex topology

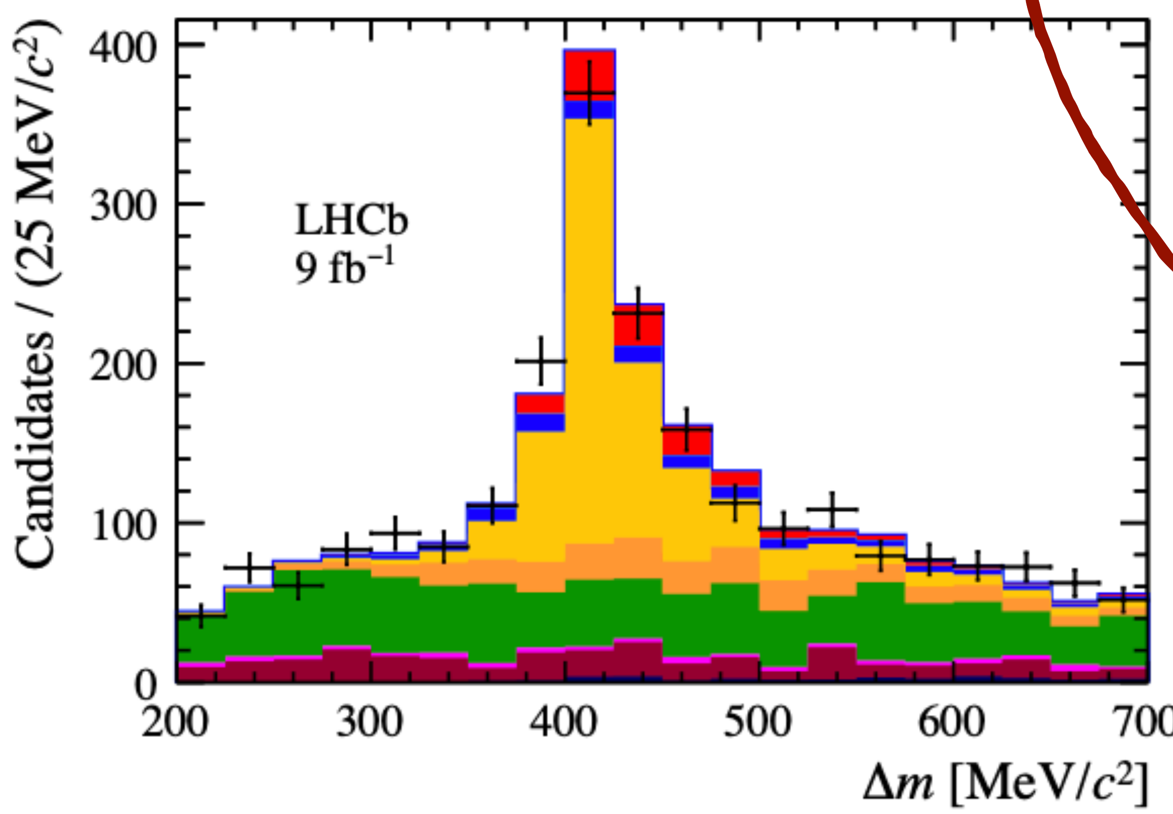
→ Normalisation BR from recent LHCb [JHEP 08 (2024) 165].

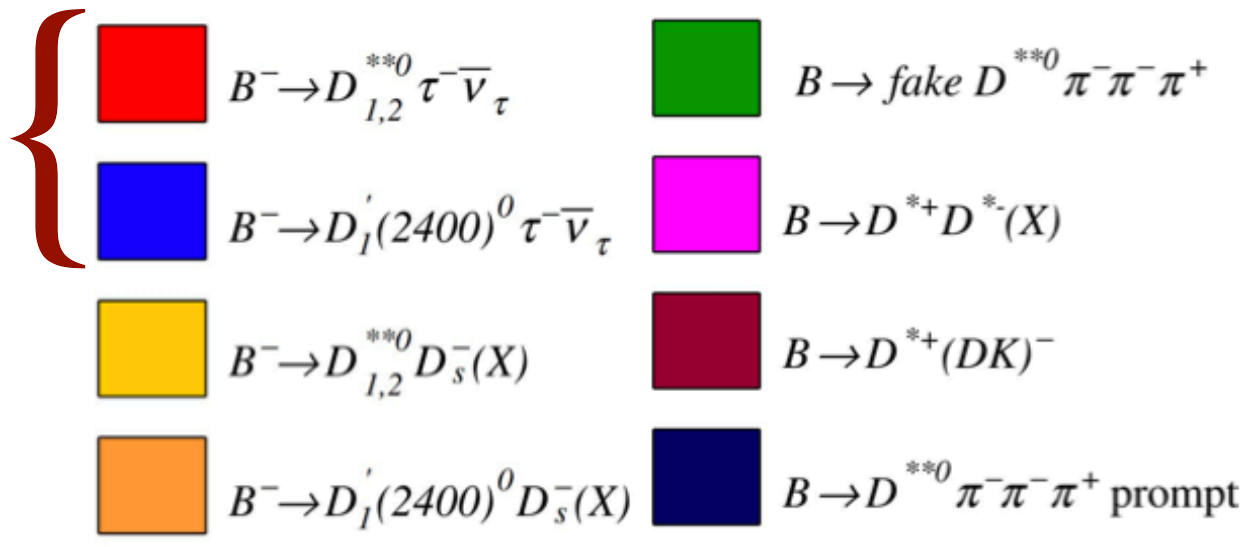
- **3D template fit:**
  - ❖ $\Delta m = m(D^{*+}\pi^-) - m(D^{*+})$
  - ❖ Anti-D_s^+ BDT output
  - ❖ $q^2 = (p_B - p_{D^{*+}})^2$

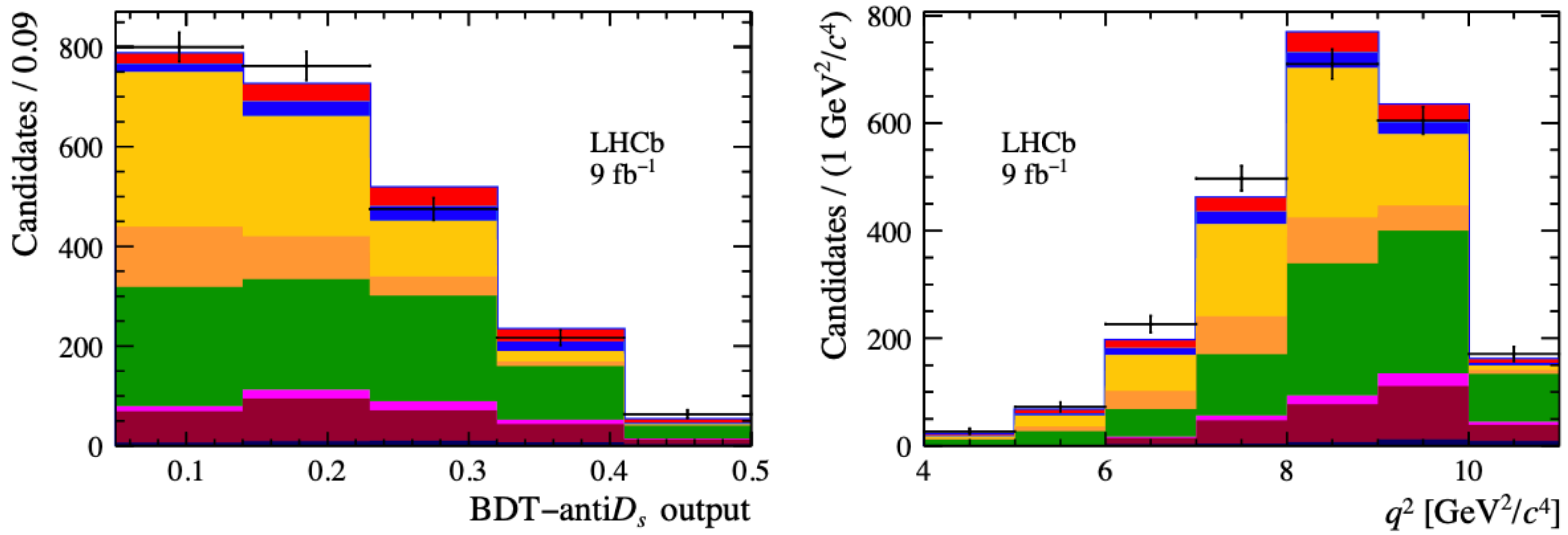
- Templates modelled with simulation and data.
- Control studies to **suppress**, **model** and **correct backgrounds**.

Signal templates :

- $D_{1,2}^{**0} = D_1(2420)^0 + D_2(2460)^0$
- $D_1'(2400)^0$
- Relative fractions fixed to predictions.







$N(B^- \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau) = 123 \pm 23$ & $N(B^- \to D^{**0}\tau^-\bar{\nu}_\tau) = 120 \pm 34$

[PHYS. REV. LETT. 135 (2025) 021802]

$B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ RESULTS

[1] PRD 97, 075011 (2018).

[2] JHEP 05 (2022) 29

[3] arXiv:2102.11608

Search result:

3.5σ significance for $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$

Branching fraction result:

$$BR(B^- \to D^{**0}_{1,2}\tau^-\bar{\nu}_\tau) \times BR(D^{**0}_{1,2} \to D^{*+}\pi^-)$$

$$= (0.051 \pm 0.013(\text{stat}) \pm 0.006(\text{syst}) \pm 0.009(\text{ext}))\ \%$$

LFU result:

$$R(D^{**0}_{1,2}) = \frac{BR(B^- \to D^{**0}_{1,2}\tau^-\bar{\nu}_\tau)}{BR(B^- \to D^{**0}_{1,2}\mu^-\bar{\nu}_\mu)}$$

$$= 0.13 \pm 0.03(\text{stat}) \pm 0.01(\text{syst}) \pm 0.02(\text{ext})$$

★ $R(D^{**0}_{1,2})$ **compatible with SM prediction** 0.09 ± 0.02 [1-3].

- ➡ Implies that deviation of from SM in $R(D^*)$ is not due to underestimation of $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decays.

★ **Updating D^{**0} yield in $R(D^{*-})$ hadronic.**

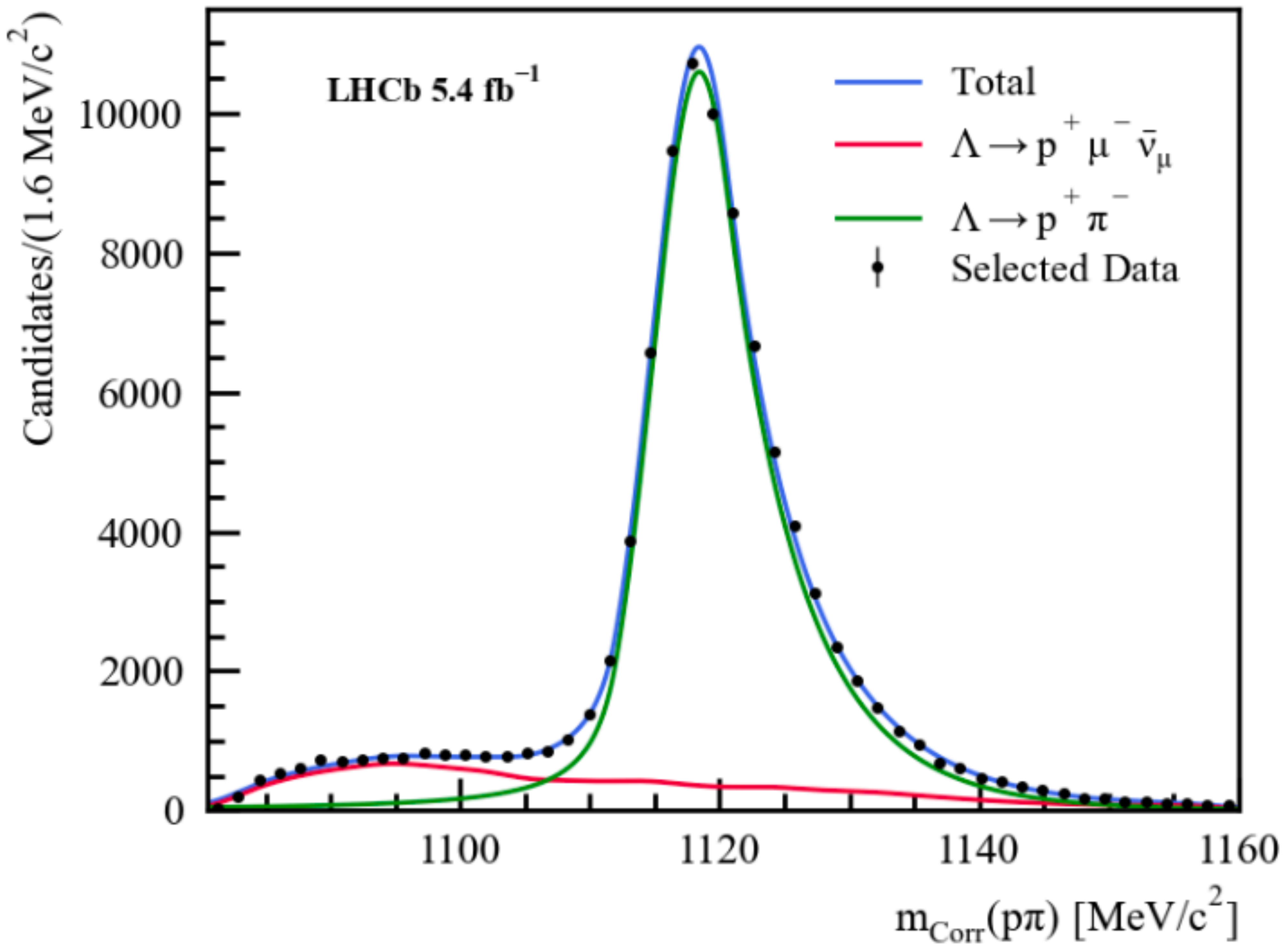
- ➡ New feed-down fraction of $(8.9 \pm 2.1)\ \%$.
- ➡ Compatible with assumed $3.5\ \%$ at 2.6σ.
- ➡ Shift in $R(D^*)$ is well within 1σ .

★ **Important input for future measurements.**

$$\Lambda \rightarrow p\mu^{-}\bar{\nu}_{\mu}$$

MEASUREMENT OF HYPERON $\Lambda \to p\mu^-\bar{\nu}_\mu$ DECAY

- **Measurement of $\Lambda \to p\mu^-\bar{\nu}_\mu$ normalised to $\Lambda \to p\pi$ @LHCb.**
  - Presented at EPS-HEP in July, 2025.
    - ➡ paper in preparation.
  - Run 2 data (2016-2018) with $\mathscr{L}_{\text{int}} = 5.4\ \text{fb}^{-1}$.



- **World best $BR(\Lambda \to p\mu^-\bar{\nu}_\mu)$ measurement with $\sigma_{\text{tot}} \sim 6.9\,\%$:**

$$(1.462 \pm 0.016\,(\text{stat}) \pm 0.100\,(\text{syst}) \pm 0.011\,(\text{norm})) \times 10^{-4}$$

  - Agrees with BESIII result [Phys. Rev. Lett. 127, 121802].

- **Indirect V_{us} measurement using LQCD results** [arXiv:2507.09970]:

$$V_{us} = 0.222 \pm 0.012 \text{ implying } \sqrt{V_{ud}^2 + V_{us}^2 + V_{ub}^2} = 0.9987 \pm 0.0028$$

  - Large uncertainty compared to PDG value based on two kaon measurements, however, they disagree with $\sim 3\sigma$.

- **LFU ratio:**
  - Improved measurement lead to more stringent bound on:

$$R_{\mu e}(\Lambda) = \frac{BR(\Lambda \to p\mu^-\bar{\nu}_\mu)}{BR(\Lambda \to pe^-\bar{\nu}_e)} = 0.175 \pm 0.012$$

Electron mode has been measured precisely

  - Agrees with **SM prediction at 0.9σ** [arXiv:2507.09970].

CONCLUSION AND OUTLOOK

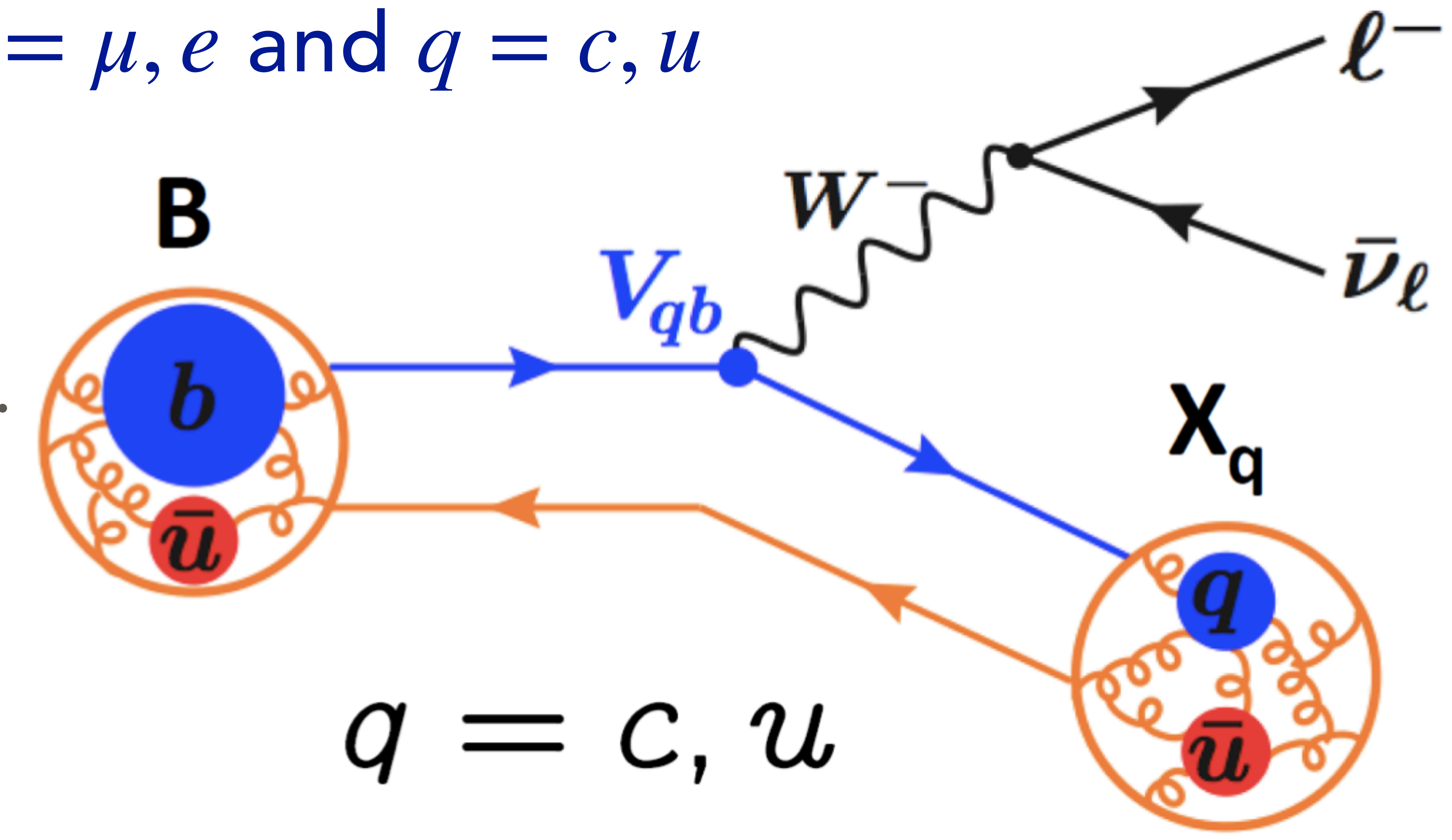
- Presented **recent LHCb results** on **charged-current decays.**
  - Many more measurements are in the **LHCb pipeline**:
    - **LFU**: $R(D^*) - (e, \mu)$, $R(D_s^*)$, $R(J/psi)$…
    - **Angular**: $B \to D^*\mu\nu$, $B \to D^*\tau\nu$, $\Lambda_b \to \Lambda_c^*\mu\nu$..
    - **CKM**: $B \to \rho^0\mu\nu_\mu$, $B_s \to K\mu\nu_\mu$…
  - **Run 3 analyses** are also in progress.

Thank you for your attention!

EXTRA SLIDES

TESTING LFU WITH CC DECAYS OF B HADRONS

- **Ratio of semileptonic decays** $b \to q\tau\nu_\tau / b \to ql\nu_l$ **with** $l = \mu, e$ **and** $q = c, u$



→ **highly sensitive to NP** (3rd generation fermions).

→ **high BRs, in particular, SL $b \to c$ decays** (e.g. $BR(B \to D^* l\nu) \sim 5\,\%$).

- Quarks are **confined** inside hadrons.

  → Decay process is affected by the **strong interaction.**

- Fortunately, the **SL decay rate can be factorised** into a hadronic and leptonic part:

$$\Gamma \propto |V_{cb}| \times F(q^2)$$

Hadronic form factors

CKM matrix element

- Enabling a **clean LFU observable** where CKM and hadronic form factor **uncertainties largely cancel out.**

$$R(X_c) = \frac{BR(X_b \to X_c \tau^- \bar{\nu}_\tau)}{BR(X_b \to X_c l^- \bar{\nu}_l)}$$

"Signal"

"Normalisation"

$$X_b = B^0, B^+, B_s^0, B_c^+, \Lambda_b^0$$

$$X_c = D^0, D^+, D_s^+, D^{*+/0}, D^{**+/0}, \Lambda_c^+, \Lambda_c^{*+}, J/\psi$$

MEASURING SEMILEPTONIC DECAYS @LHCB

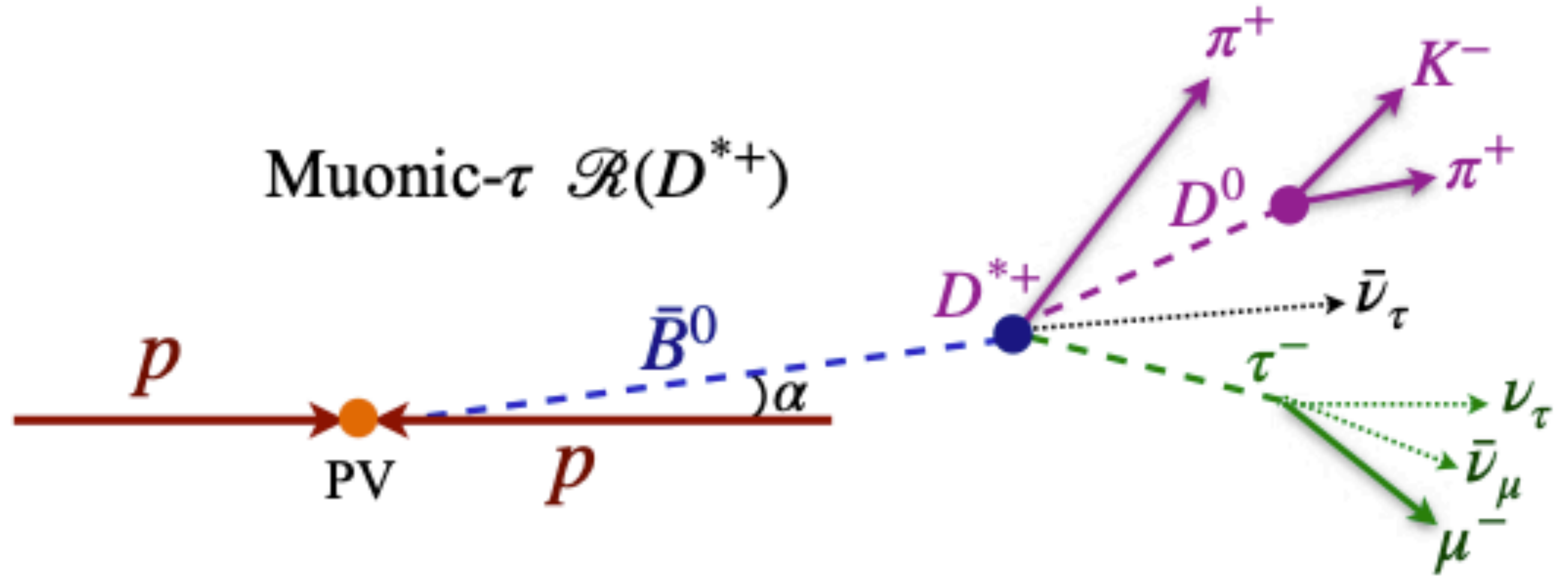
➡ **Pros @LHCb:** High $b\bar{b}$ production → large signal samples.

➡ **Cons @LHCb:** b hadron and τ lepton are partially reconstructed → large background rates.

Two reconstruction approaches for the τ lepton

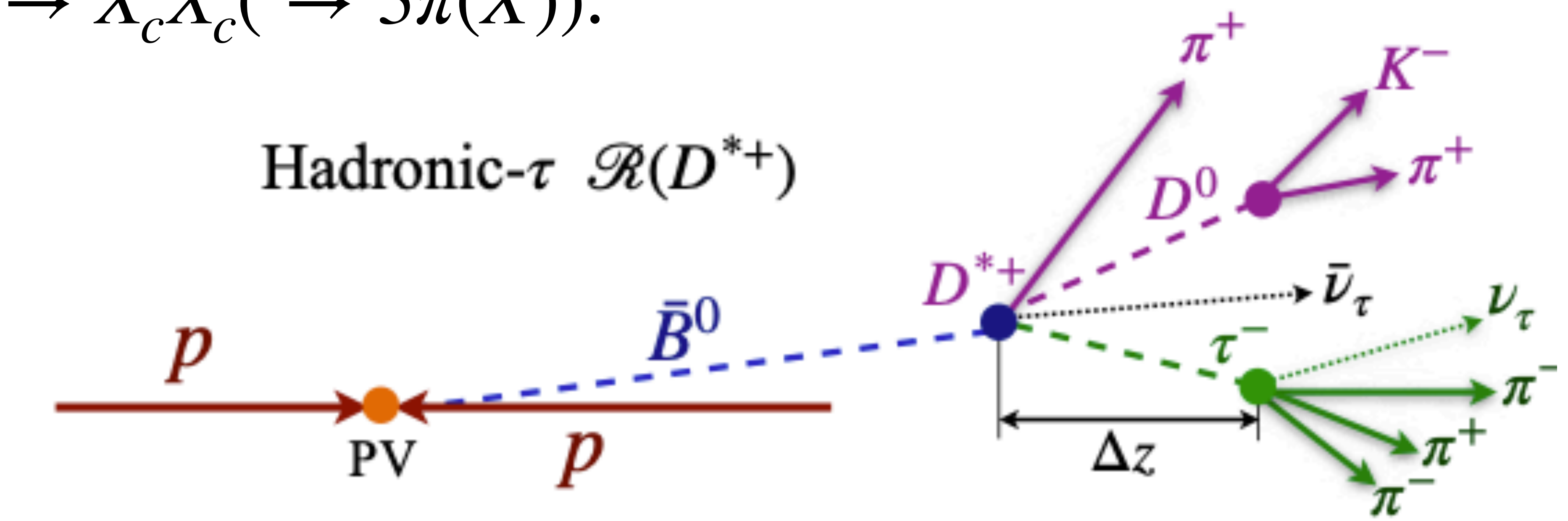
Muonic $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ ($BR \sim 17\,\%$)

- **Same visible final state** for signal and normalisation.
  - Direct measurement of $R(X_c)$.
- **τ vertex is not reconstructed**.
  - B rest frame approximation: $p_z(X_b) = m_b/m_{X_c\mu} \times p_z(X_c\mu)$
  - High rate of partially reconstructed b-hadron decays.



Hadronic $\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$ ($BR \sim 13.5\,\%$)

- **Different visible final state** for signal and normalisation.
  - Additional normalisation mode.
  - External BR input for muonic mode.
- **τ vertex is reconstructed** → reject backgrounds.
- Main backgrounds are "double-charm" decays $X_b \to X_c' X_c(\to 3\pi(X))$.



$R(D^0)$ & $R(D^*)$ MUONIC, 2023

- **Run 1 data (2011-2012)** with $\mathscr{L}_{\text{int}} = 3\ \text{fb}^{-1}$.
- **First simultaneous $R(D^0)$ & $R(D^*)$ measurement:**

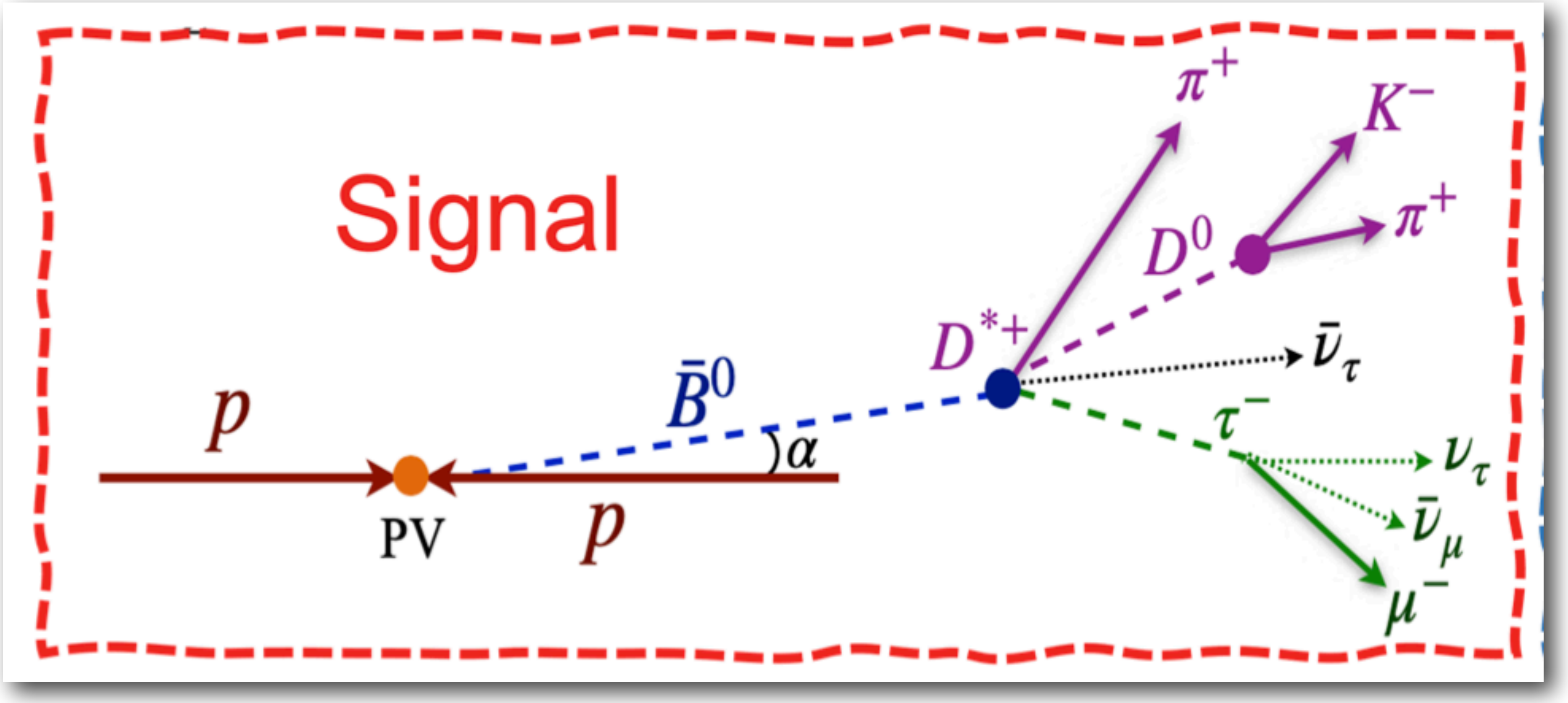
→ Updates a previous LHCb analysis [Phys. Rev. Lett. 115, 159901]

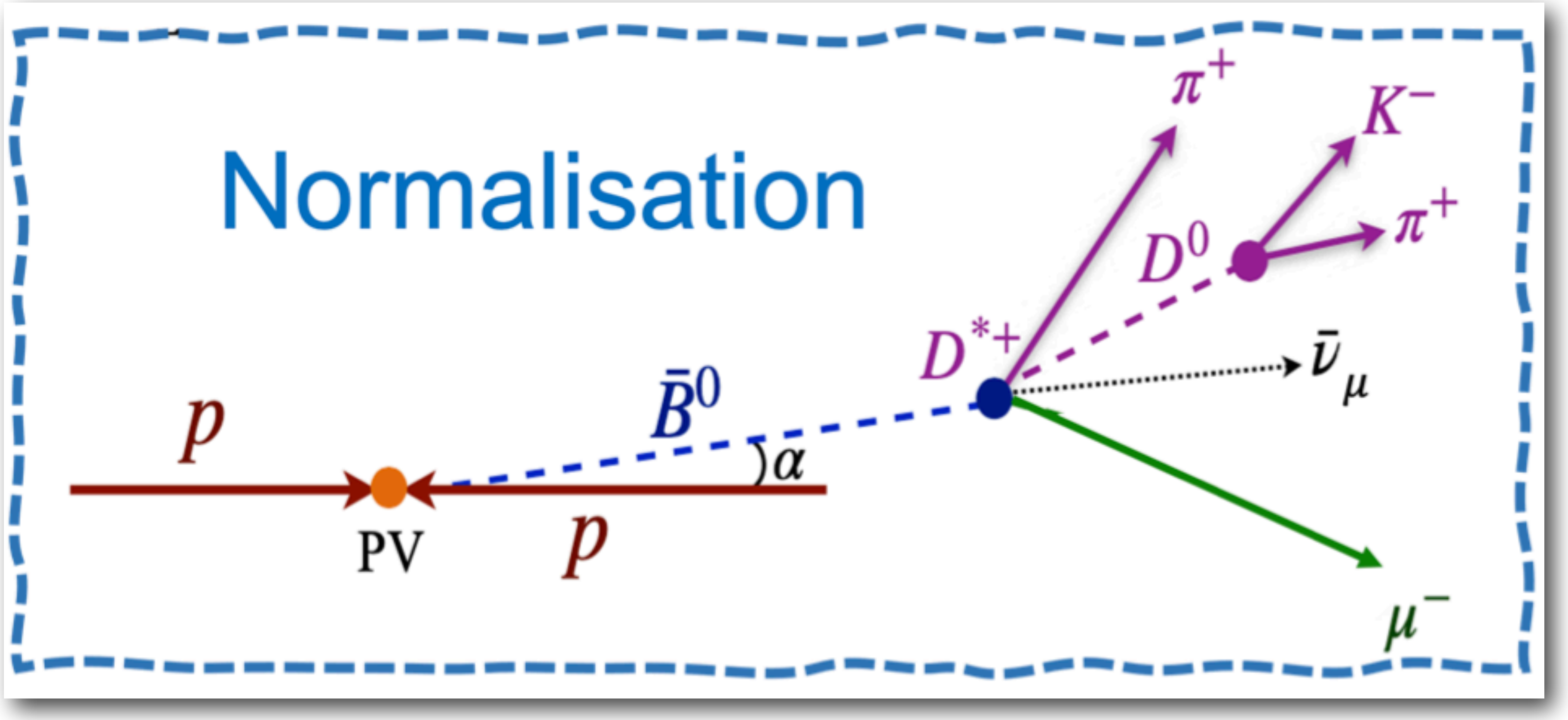
$$R(D^{(*)}) = \frac{BR(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{BR(\bar{B} \to D^{(*)}\mu^-\bar{\nu}_\mu)}, \quad D^{(*)} = D^0, D^{*+}, D^{*0}$$

$\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$ & $D^{*+} \to D^0\pi^+$ & $D^0 \to K^-\pi^+$

→ muonic and tauonic states have same visible final state.

Signal and normalisation with D^{*+} state
[A. Mathad, arXiv:2305.08133]



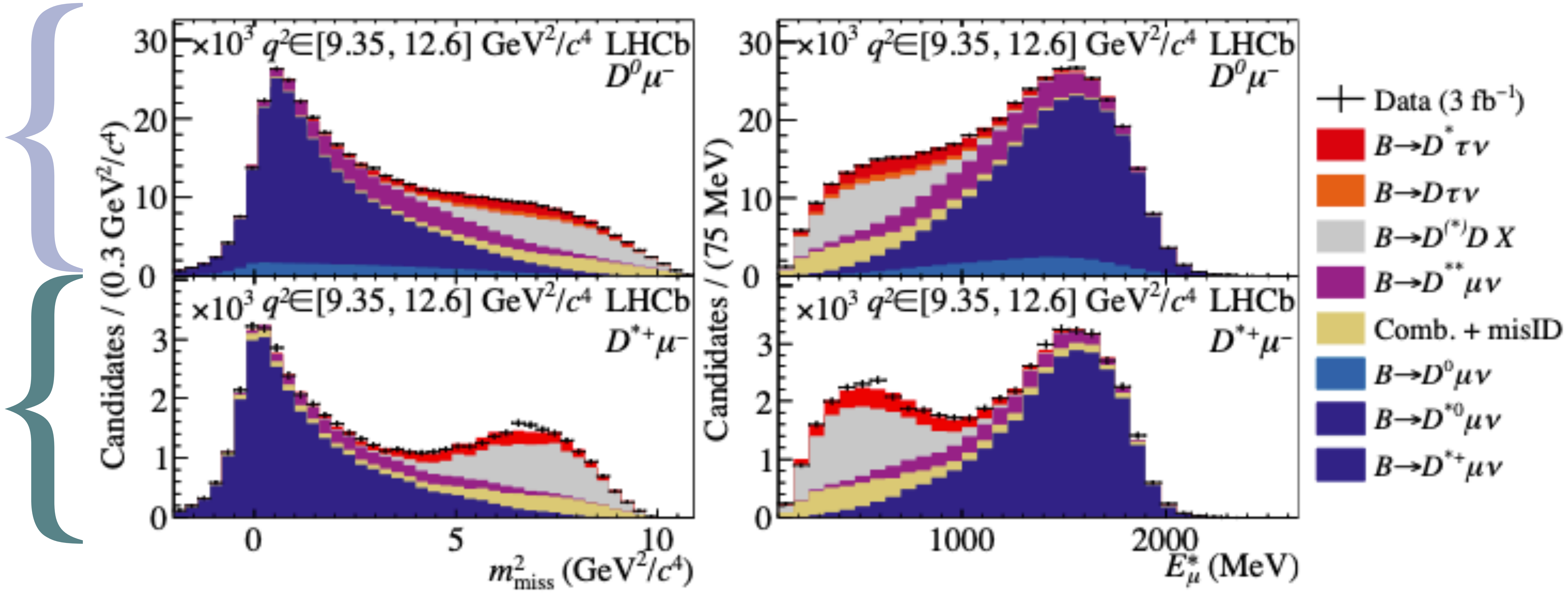


$R(D^0)$ & $R(D^*)$ MUONIC, 2023

- **3D fit in q^2, E_μ^* and m_{miss}^2 :**
  - Two disjoint $D^0\mu^-$ and $D^{*+}\mu^-$ samples.
  - **Components** modelled with **simulation** and **data.**
  - Two **signal** + six **background enhanced control regions** are fit simultaneously.

    → Background corrections are propagated from control to signal regions.

Fit in $D^0\mu^-$ and $D^{*+}\mu^-$ samples (signal region)



$\sigma_{\text{stat}} \sim 14\,\%$ & $\sigma_{\text{syst}} \sim 15\,\%$

$$R(D^*) = 0.281 \pm 0.018(\text{stat}) \pm 0.024(\text{syst})$$

$\sigma_{\text{stat}} \sim 6\,\%$ & $\sigma_{\text{syst}} \sim 9\,\%$

$$R(D^0) = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{syst})$$

$\rho = -0.43$

Dominant systematics:

- Limited template sizes.
- "Feed-down" form factors.
- Modelling "double-charm".

$\sim 2\sigma$ from SM (2023)

$R(D^{*-})$ HADRONIC, 2023

- **Run 2 data (2015-2016)** with $\mathscr{L}_{\text{int}} = 2\ \text{fb}^{-1}$.

- $R(D^{*-})$ **measurement**:

→ Similar Run 1 LHCb analysis [Phys. Rev. Lett. 120, 171802 (2018)] (factor ~2 higher signal yield).

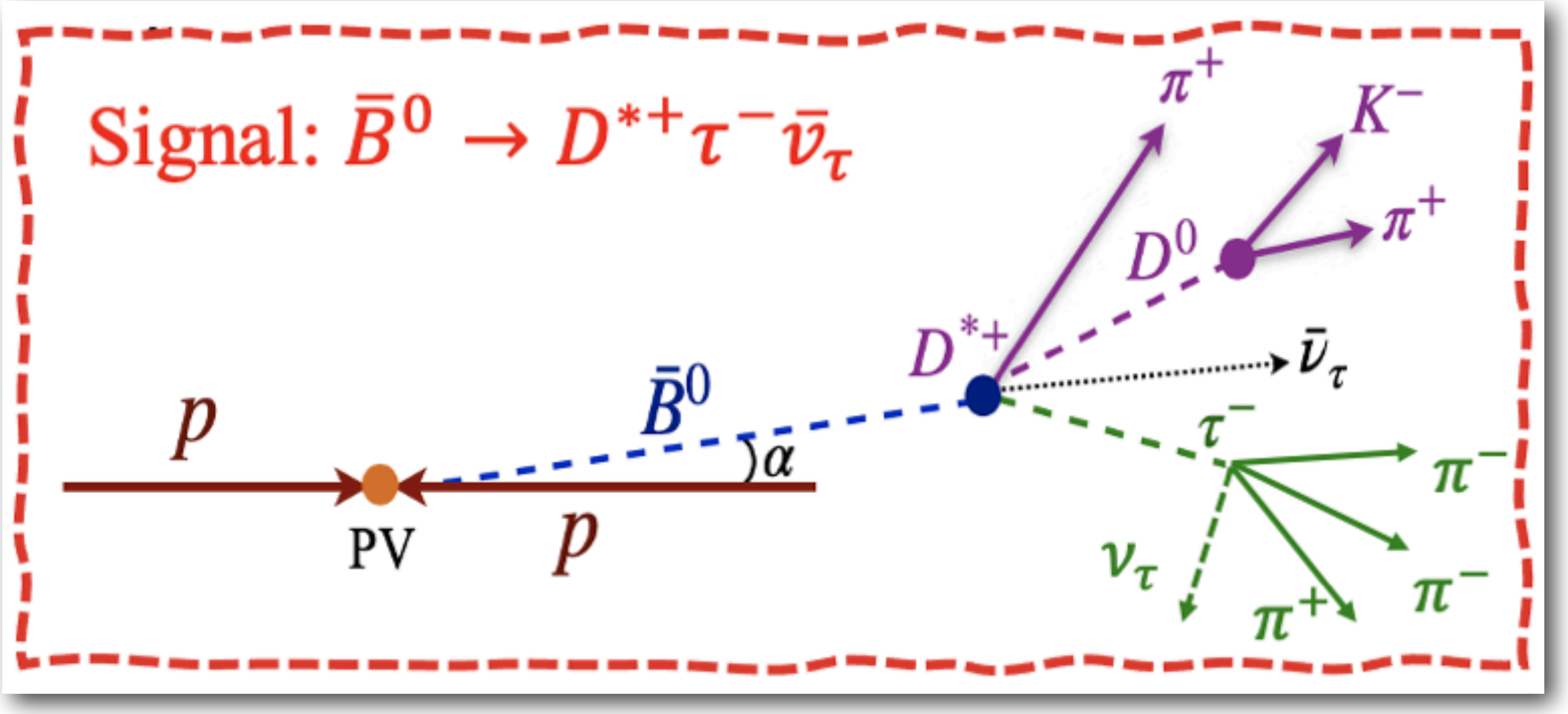
$$R(D^{*-}) = \frac{BR(B^0 \to D^{*-}\tau^+\nu_\tau)}{BR(B^0 \to D^{*-}3\pi)} \times \frac{BR(B^0 \to D^{*-}3\pi)}{BR(B^0 \to D^{*-}\mu^+\nu_\mu)},$$

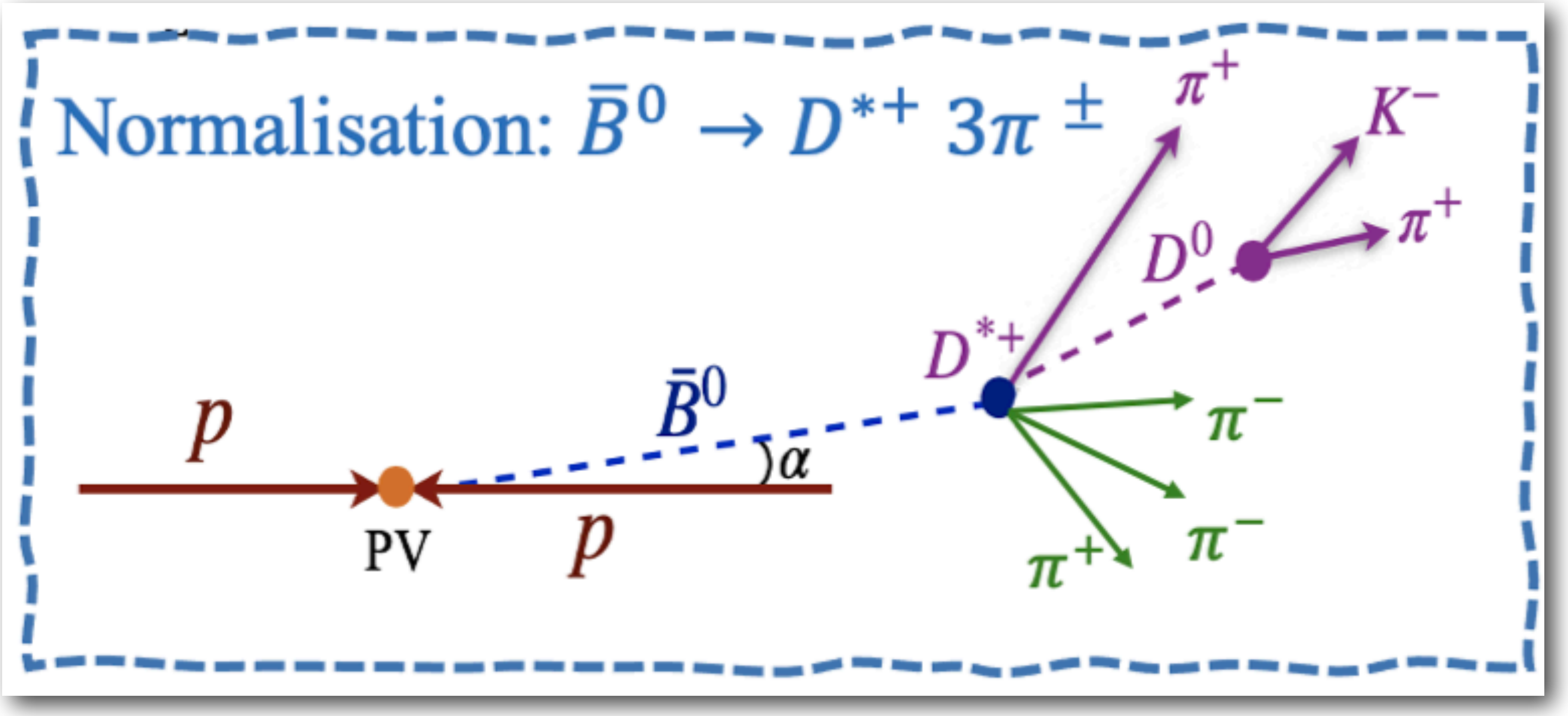
$\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$ & $D^{*-} \to \bar{D}^0\pi^-$ with $\bar{D}^0 \to K^+\pi^-$

- $B^0 \to D^{*-}3\pi$ chosen to reduce systematic uncertainties (detector & reconstruction effects).

- Using external $BR(B^0 \to D^{*-}3\pi)$ and $BR(B^0 \to D^{*-}\mu^+\nu_\mu)$.

Signal and normalisation with D^{*+} state
[A. Mathad, arXiv:2305.08133]





[PHYS. REV. LETT. 135 (2025) 021802]

STUDYING $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ DECAYS

- **Motivation:**

  One of the **largest systematic uncertainties** in $R(D^{(*)})$ is the **limited knowledge of $B \to D^{**}\tau^-\bar{\nu}_\tau$ contamination** of $B \to D^{*+}\tau^-\bar{\nu}_\tau$ decays.

- **Analysis goals:**

  1. Search for $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decays where $D^{**0} = D_1'(2400)^0, D_1(2420)^0, D_2(2460)^0$.
  2. Measure $BR(B^- \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau) \times BR(D_{1,2}^{**0} \to D^{*+}\pi^-)$ where $D_{1,2}^{**0} = D_1(2420)^0, D_2(2460)^0$.
  3. Determine $R(D_{1,2}^{**0})$ with external $BR(B^- \to D_{1,2}^{**0}\mu^-\bar{\nu}_\mu)$.

D^{**} states that could affect $R(D^{(*)})$:

→ Decay significantly into $D^*\pi$.

$D_1'(2400)^0$:
$m = (2412 \pm 9)$ MeV/c^2,
$\Gamma = (314 \pm 29)$ MeV/c

$D_1(2420)^0$:
$m = (2422.1 \pm 0.6)$ MeV/c^2,
$\Gamma = (31.3 \pm 1.9)$ MeV/c

$D_2(2460)^0$:
$m = (2461.1 \pm 0.8)$ MeV/c^2,
$\Gamma = (47.3 \pm 0.8)$ MeV/c

[PHYS. REV. LETT. 135 (2025) 021802]

SELECTION OF $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ DECAYS

- **Full Run 1 & 2 dataset** ($\mathscr{L}_{\text{int}} = 9\ \text{fb}^{-1}$).

- **Reconstruction:**

  ➡ **Signal $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$:**

  $\tau^- \to \pi^+\pi^-\pi^-(\pi^0)\nu_\nu$

  $D^{**0}_{1,2} \to D^{*+}\pi^-,\ D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+$

  ➡ **Normalisation $B^- \to D^{**0}_{1,2}D_s^{(*)-}$:**

  $D_s^- \to \pi^-\pi^+\pi^-$

  $D^{**0}_{1,2} \to D^{*+}\pi^-,\ D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+$

→ **same visible final state** and **vertex topology** as the signal & recent BR by LHCb [JHEP 08 (2024) 165]

- **Selection:**

  ★ **Trigger + pre-selection requirements.**

  ★ **τ flight distance requirement** to suppress prompt $B \to D^{**0}\pi^-\pi^-\pi^+(X)$ backgrounds.

  ★ **Three BDTs to reject:**

  (1) Fake D^{**0} candidates.

  (2) $B \to D^{*+}D_s^-(X)$ with a 5-prong D_s^- decay mimicking both D^{**0} and τ^-.

  (3) Main $D_s^- \to \pi^-\pi^+\pi^-(X)$ background mimicking τ^+ (BDT anti-Ds).

[PHYS. REV. LETT. 135 (2025) 021802]

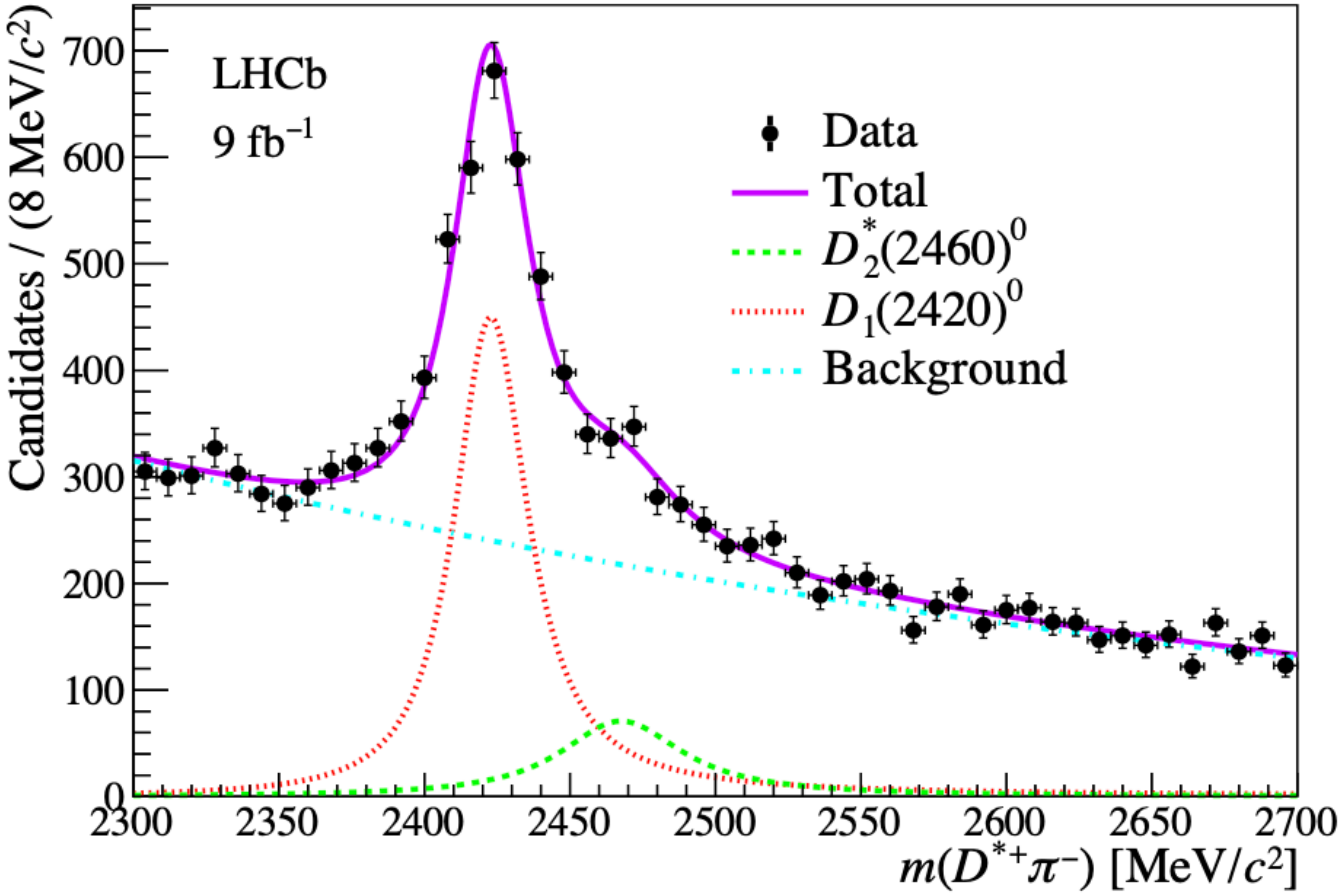
COMPOSITION OF $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ SAMPLE

- **Fitting selected $m(D^{*+}\pi^-)$ spectrum**

  → Without BDT-antiDs and $\pi^-\pi^+\pi^+$ selection.

- Fit Illustrates the $\mathbf{D_1(2420)^0}$ and $\mathbf{D_2(2460)^0}$ composition in the initial D^{**0} sample.

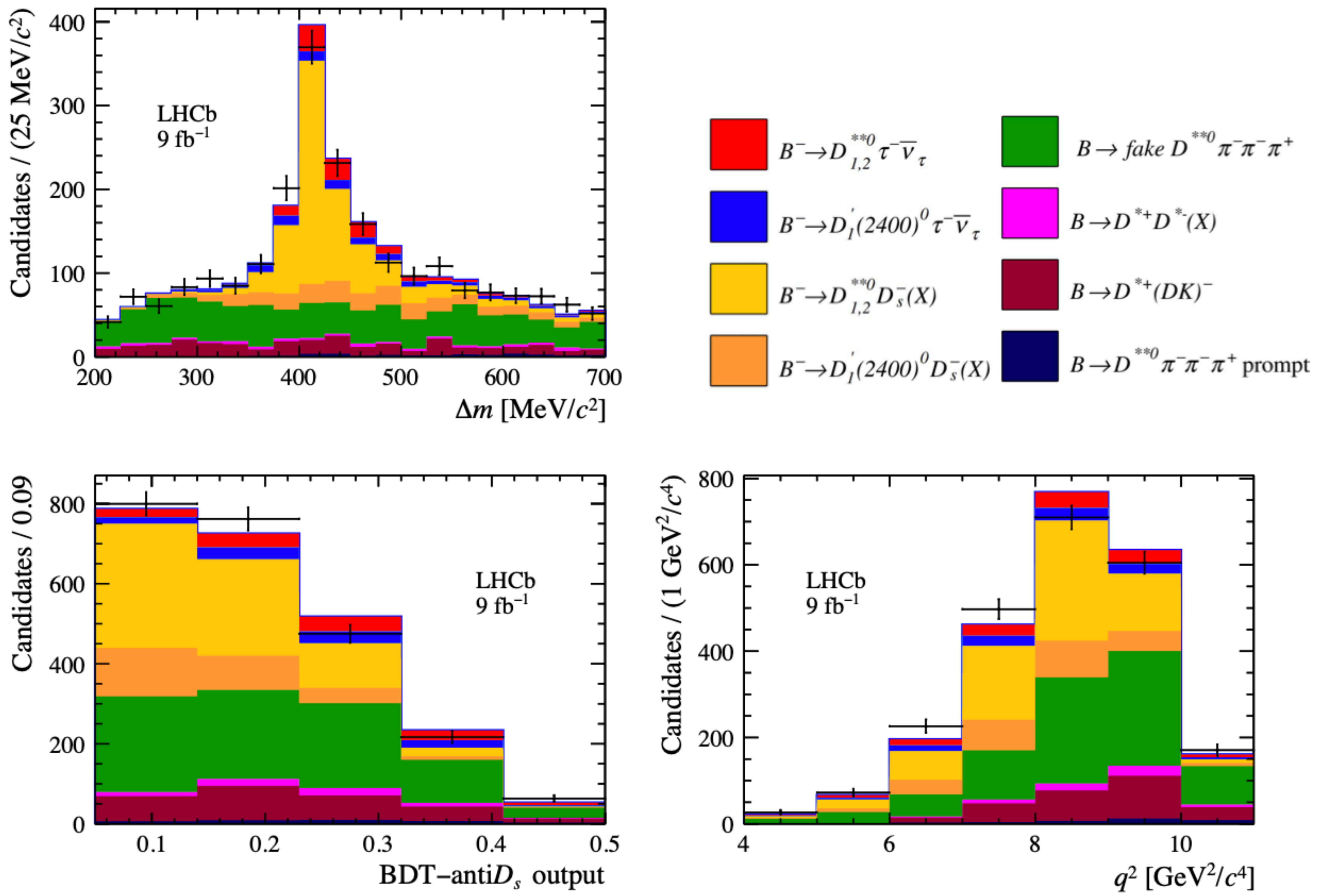
Fit is not sensitive to a potential $D_1'(2400)^0$ contribution



$N_{D_1(2420)^0} = 2456 \pm 75$ & $N_{D_2^*(2460)^0} = 633 \pm 69$

DETERMINING THE $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ YIELDS

- **3D binned template fit:**
  - $\Delta m = m(D^{**0}) - m(D^{*+})$
  - anti-D_s^+ BDT output
  - $q^2 = (p_B - p_{D^{*+}})^2 = m^2_{\tau\nu}$



$N(B^- \to D^{**0}_{1,2}\tau^-\bar{\nu}_\tau) = 123 \pm 23$ & $N(B^- \to D^{**0}\tau^-\bar{\nu}_\tau) = 120 \pm 34$

- **Signal templates** (simulation):
  - $D_1(2420)^0$ and $D_2(2460)^0$ modes combined.
  - Fixing fractions of $D_1(2420)^0$, $D_2(2460)^0$ and $D_1'(2400)^0$ to predictions.
- **Background templates** (simulation + data):
- **Control data samples:**
  - D^0 and D^{*+} mass sidebands → subtract fake D^0 and D^{*+}.
  - Wrong sign $D^{*\pm}\pi^\pm$ candidates → model fake D^{**0} backgrounds.
  - Selecting $m(\pi^+\pi^-\pi^+)$ around $m(D_s^+)$ and removing BDT-antiDs requirement → determine relative D_s^-, D_s^{*-} and D_s^{**-} proportions and use it as constraints in fit.

PROJECTIONS FOR THE EXPECTED PRECISION @LHCB

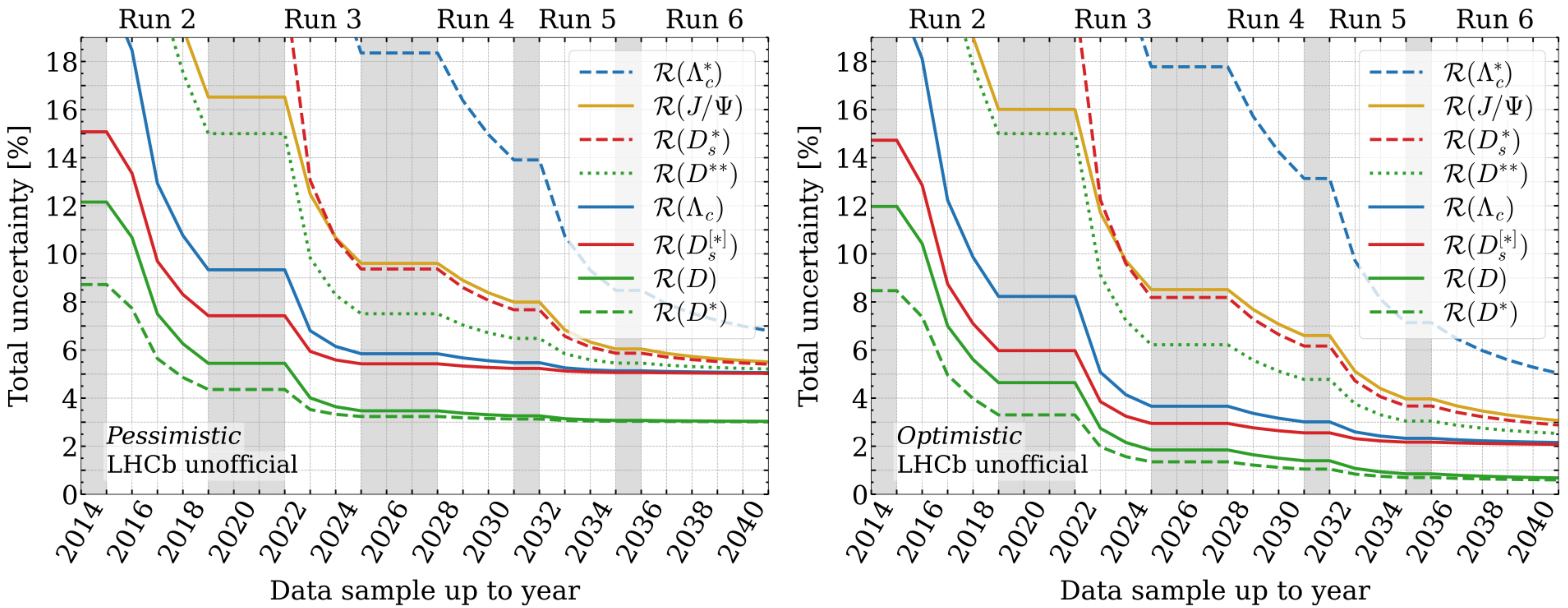


Figure 34 Projections for the expected precision on the measurement of selected $\mathcal{R}(H_c)$ ratios at LHCb as a function of the year in which the corresponding data sample becomes available. The order of the curves in the legend corresponds to the order of the curves on the plot for the year 2026. Left: pessimistic scenario for an irreducible systematic uncertainty of 3% on $\mathcal{R}(D^{(*)})$ and 5% on the other ratios. Right: optimistic scenario for an irreducible systematic uncertainty of 0.5% on $\mathcal{R}(D^{(*)})$ and 2% on the other ratios. These extrapolations are based on the current muonic-τ measurements of $\mathcal{R}(D^{(*)})$ and $\mathcal{R}(J/\psi)$, as well as the forthcoming hadronic-τ measurement of $\mathcal{R}(D_1^0)$ for the $\mathcal{R}(D^{**})$ curve. The symbol $\mathcal{R}(D_s^{[*]})$ refers to the sum of the D_s and D_s^* yields, as described in the text. The $\mathcal{R}(\Lambda_c^*)$ entry in the legend refers to $\mathcal{R}(\Lambda_c^*(2625))$. The shaded regions correspond to the long shutdowns during which there is no data taking at the LHC and have been updated including the latest estimates (Béjar Alonso *et al.*, 2020).

RELATIVE UNCERTAINTIES ON SELECTED RESULTS

[PHYS. REV. LETT. 134 (2025) 061801]

- **First simultaneous $R(D^+)$ & $R(D^{*+})$ @LHCb, 2025**

~17% ~19%

$$R(D^+) = 0.249 \pm 0.043(\text{stat}) \pm 0.047(\text{syst})$$

~20% ~21%

$$R(D^{*+}) = 0.402 \pm 0.081(\text{stat}) \pm 0.085(\text{syst})$$

[PHYS. REV. D 108 (2023), 012018]

- **$R(D^{*-})$ with hadronic @LHCb, 2023**

~6% ~6% ~5%

$$\boldsymbol{R(D^{*-}) = 0.260 \pm 0.015(\text{stat}) \pm 0.016(\text{syst}) \pm 0.012(\text{ext})}$$

[PHYS. REV. D 110 (2024), 092007]

- **F_L^{D*} hadronic @LHCb, 2024**

~15% ~7%

$$\boldsymbol{F_L^{D*} = 0.41 \pm 0.06(\text{stat}) \pm 0.03(\text{syst})}$$

- **Belle result, 2019**

~13% ~7%

$$\boldsymbol{F_L^{D*} = 0.60 \pm 0.08(\text{stat}) \pm 0.04(\text{syst})}$$

[PHYS. REV. LETT. 135 (2025) 021802]

~25% ~12% ~18%

$$BR(B^- \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau) \times BR(D_{1,2}^{**0} \to D^{*+}\pi^-) = (0.051 \pm 0.013(\text{stat}) \pm 0.006(\text{syst}) \pm 0.009(\text{ext}))\ \%$$