Recent results from LHCb on charged-current decays of *b*-hadrons

Lepton-Photon, Madison, 26th August 2025

Ching-Hua Li on behalf of the LHCb collaboration

Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

Outline

- **Introduction**
  - LHCb detector
  - b-hadrons charged-current decays and lepton flavour universality
  - Lepton flavour universality test in LHCb semi-leptonic physics
- **Recent results**
  - Measurements of $R(D^{*-})$ and $R(D^{-})$ using part of Run 2 data
  - Evidence of $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ with Run 1&2 data
- **New results :**
  - $\Lambda \to p\mu^-\bar{\nu}_\mu$ branching ratio measurement with Run 2 data
- **Conclusion**

Introduction

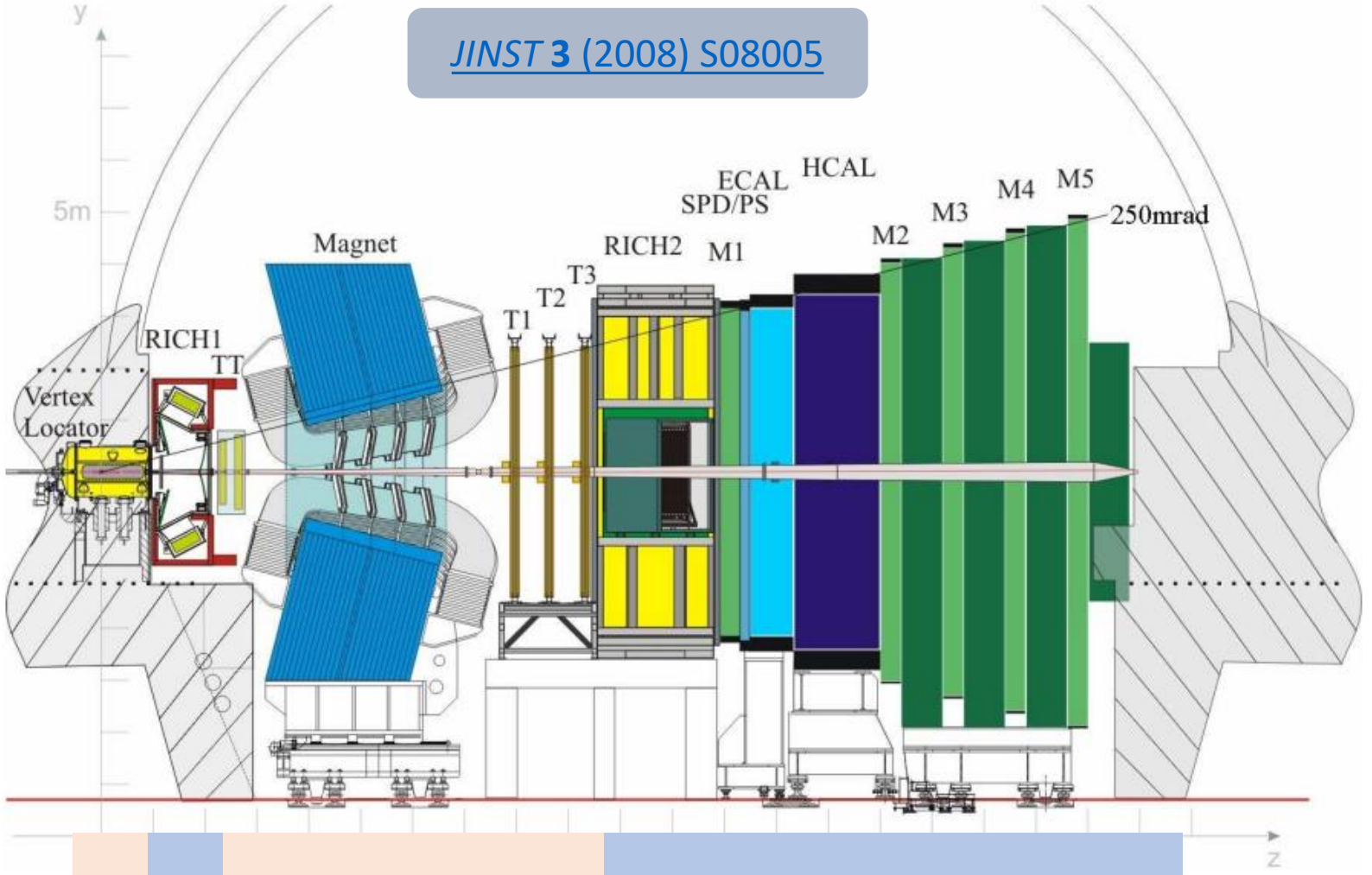
LHCb detector

- Single-arm spectrometer covering most of the region where $\sigma(pp \to b\bar{b}X)$ is maximal

- In Run 1 and 2, around 2×10^{12} and 8×10^{12} $b\bar{b}$ pairs produced in LHCb acceptance, respectively.

- Excellent vertexing and PID capabilities to perform high precision measurement of semi-leptonic B decay.

JINST **3** (2008) S08005



$\sigma_p/p \sim (0.1 - 0.6)$ GeV/c at 5 – 100 GeV/c

Tracking

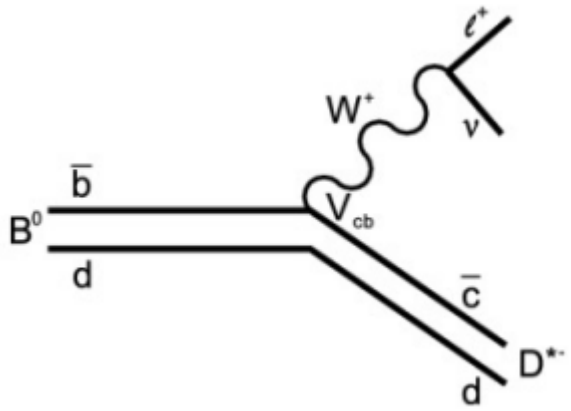
μ ID $\in 97\%$, 0.6% $\pi \to \mu$
e ID $\in 95\%$, 1% $\pi \to e$
K ID $\in 90\%$, 3% $\pi \to K$

Particle identification

Why *b*-hadrons charged-current decays ?

Test of Lepton Flavour Universality

***b*–hadron production**



CKM parameters
(e.g. $|V_{cb}|$, $|V_{ub}|$ measurement)

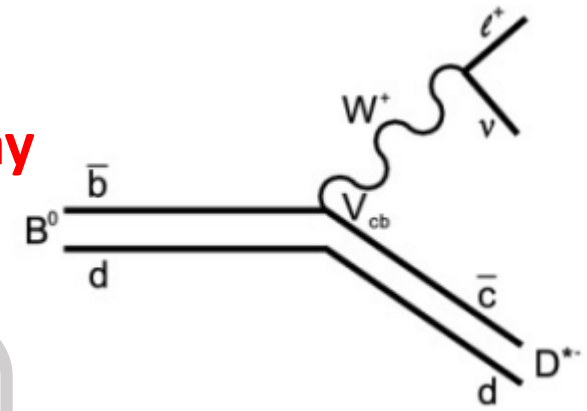
Form factor parameters and Wilson coefficients

Why *b*-hadrons charged-current decays ?

Test of Lepton Flavour Universality

b–hadron production

Will focus on this topic today



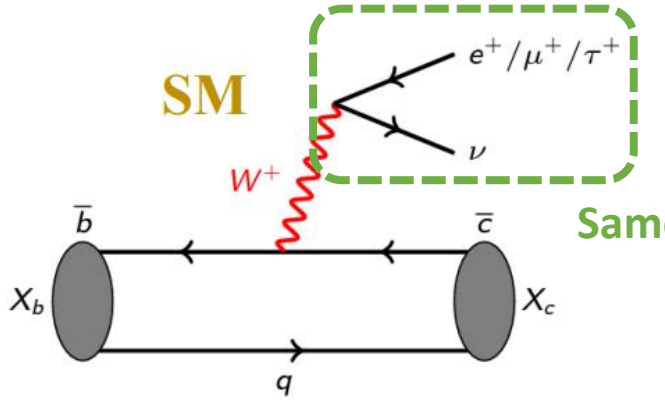
CKM parameters
(e.g. $|V_{cb}|, |V_{ub}|$ measurement)

Form factor parameters and Wilson coefficients

Lepton Flavour Universality (LFU) in the SM

What is LFU ?

In Standard Model (SM), electroweak couplings to each lepton generation are **identical.**

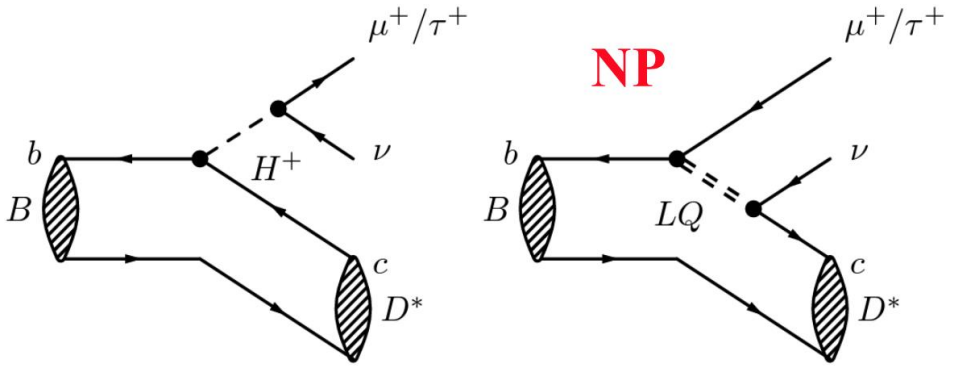


Same coupling strength

How can LFU be violated ?

The couplings could be affected by New Physics (NP) contributions.

e.g. Leptoquarks, two Higgs doublet, non-universal left-right model



Test LFU with charged-current decays in LHCb

LFU can be tested in decay ratios

$$R(X_c) = \frac{BF(X_b \to X_c l \nu)}{BF(X_b \to X_c l' \nu)}$$, $X_{b(c)}$ **is a meson or baryon containing a *b* or *c* quark**

Advantages

High precision :
Large statistics due to $b \to c$ transition and large cross-section of $pp \to b\bar{b}$ in LHCb.

Theoretically clean :
Uncertainties from common systematic and hadronic form factor mostly cancel by measuring the decay ratio

Challenges

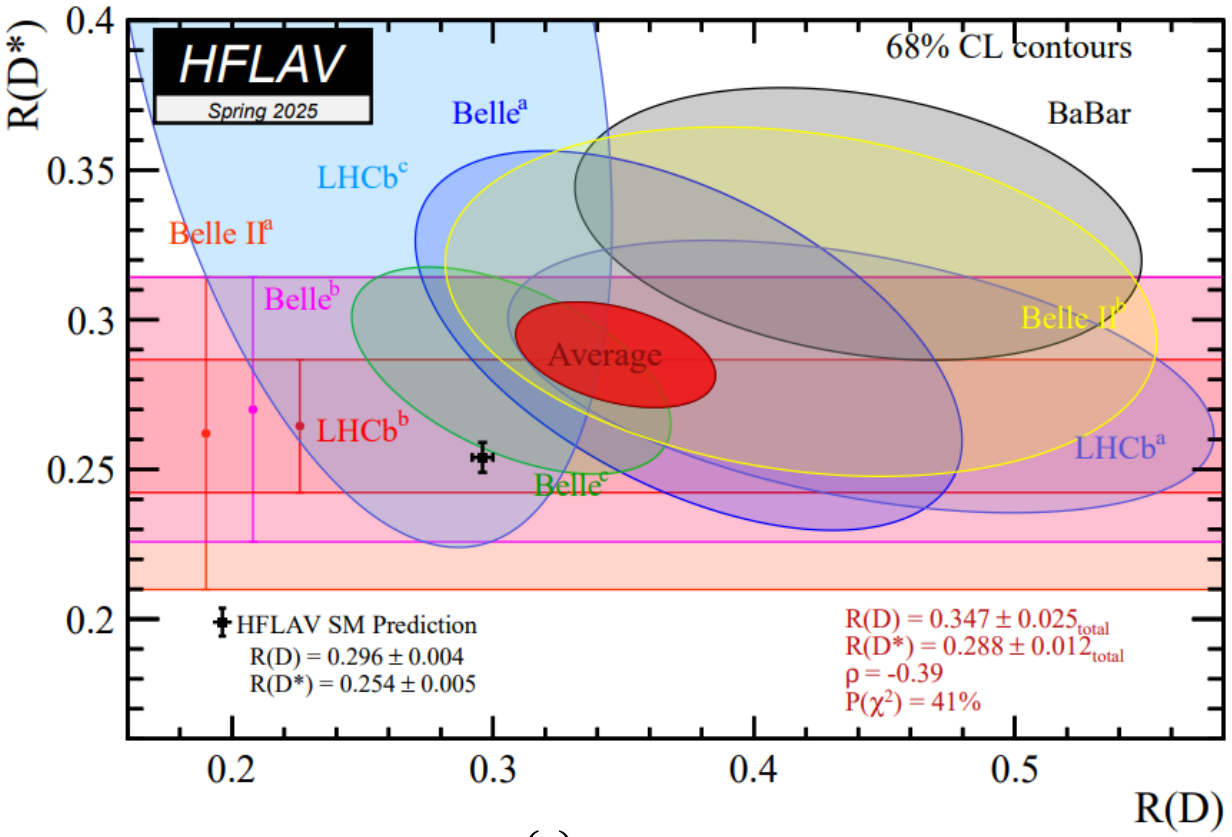
Missing neutrinos in the final state **:**
Affects the resolution of the observables

Large background contamination due to partial reconstruction.

Uncertainties from template statistics :
Large simulation samples needed for modelling signal and background.

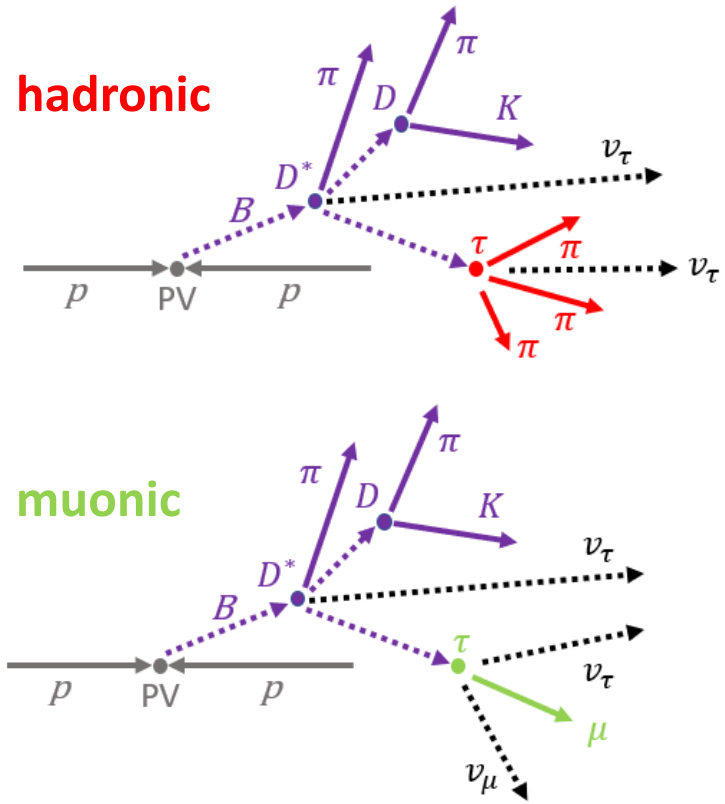
Experimental and theoretical status for $R(D^{(*)})$

Link of HFLAV $R(D^{(*)})$ average in 2025



3.8 σ tension in $R(D^{(*)})$ measurement with SM prediction

Currently, we have $R(D^{(*)-})_{\tau/\mu}$ measurements using **hadronic** and **muonic** τ decays in LHCb.



Semi-leptonic LFU measurements in LHCb

Muonic τ decays

Run 1 (2015) PRL 115 11803
$R(D^{*+}) = 0.336 \pm 0.027\ (stat) \pm 0.030\ (syst)$

Run 1 (2023) PRL 131 11802
$R(D^{*}) = 0.281 \pm 0.018\ (stat) \pm 0.024\ (syst)$
$R(D^{0}) = 0.441 \pm 0.060\ (stat) \pm 0.066\ (syst)$

Part of Run 2 (2024) PRL 134 061801
$R(D^{*+}) = 0.402 \pm 0.081\ (stat) \pm 0.085\ (syst)$
$R(D^{+}) = 0.249 \pm 0.043\ (stat) \pm 0.047\ (syst)$

Run 1 (2018) PRL 120 121801
$R(J/\Psi) = 0.71 \pm 0.17\ (stat) \pm 0.18\ (syst)$

Hadronic τ decays

Run 1 (2018) PRL 120 171802
$R(D^{*+}) = 0.291 \pm 0.019\ (stat) \pm 0.026\ (syst) \pm 0.013\ (ext)$

Part of Run 2 (2023) PRD 108 (2023) 012018 Erratum
$R(D^{*+}) = 0.260 \pm 0.015\ (stat) \pm 0.016\ (syst) \pm 0.012\ (ext)$

Run 1 (2022) PRL 128 191803
$R(\Lambda_c^{+}) = 0.242 \pm 0.026\ (stat) \pm 0.040\ (syst) \pm 0.059\ (ext)$

Run 1 & 2 (2025) PRL 135 021802
$R(D_{1,2}^{**0}) = 0.13 \pm 0.03\ (stat) \pm 0.01\ (syst) \pm 0.02\ (ext)$

Semi-leptonic LFU measurements in LHCb

Muonic τ decays

Run 1 (2015) PRL 115 11803
$R(D^{*+}) = 0.336 \pm 0.027\ (stat) \pm 0.030\ (syst)$

Run 1 (2023) PRL 131 11802
$R(D^{*}) = 0.281 \pm 0.018\ (stat) \pm 0.024\ (syst)$
$R(D^{0}) = 0.441 \pm 0.060\ (stat) \pm 0.066\ (syst)$

Part of Run 2 (2024) PRL 134 061801
$R(D^{*+}) = 0.402 \pm 0.081\ (stat) \pm 0.085\ (syst)$
$R(D^{+}) = 0.249 \pm 0.043\ (stat) \pm 0.047\ (syst)$

Run 1 (2018) PRL 120 121801
$R(J/\Psi) = 0.71 \pm 0.17\ (stat)$ ...

Hadronic τ decays

Run 1 (2018) PRL 120 171802
$R(D^{*+}) = 0.291 \pm 0.019\ (stat) \pm 0.026\ (syst) \pm 0.013\ (ext)$

Part of Run 2 (2023) PRD 108 (2023) 012018 Erratum
$R(D^{*+}) = 0.260 \pm 0.015\ (stat) \pm 0.016\ (syst) \pm 0.012\ (ext)$

Run 1 (2022) PRL 128 191803
$R(\Lambda_c^{+}) = 0.242 \pm 0.026\ (stat) \pm 0.040\ (syst) \pm 0.059\ (ext)$

Run 1 & 2 (2025) PRL 135 021802
$R(D_{1,2}^{**0}) = 0.13 \pm 0.03\ (stat) \pm 0.01\ (syst) \pm 0.02\ (ext)$

Introduced in this talk

$R(D^{(*)-})$ measurements

$R(D^+)$ and $R(D^{*+})$ with muonic τ decays

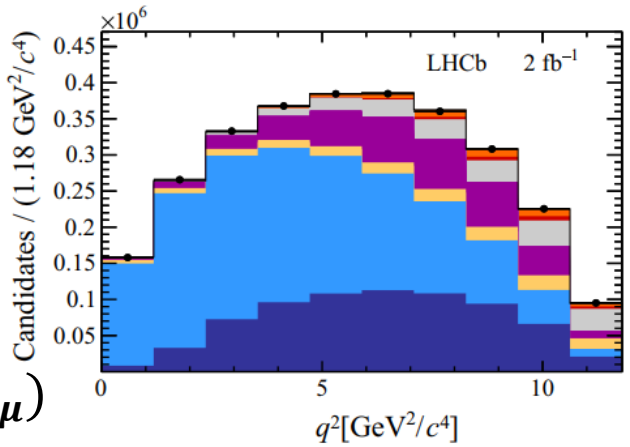
PRL 134 061801

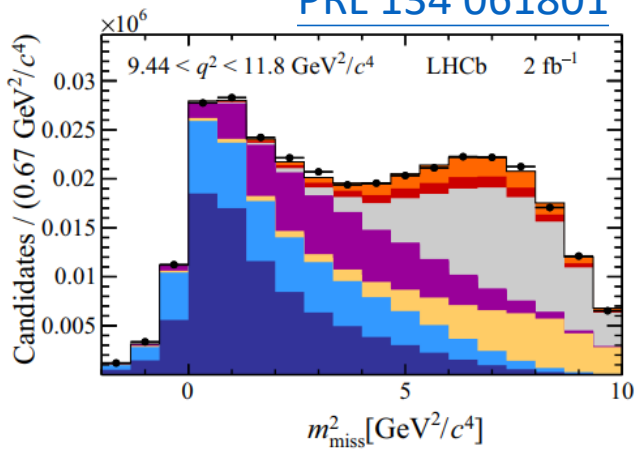
Data collected in 2015-2016 corresponding to

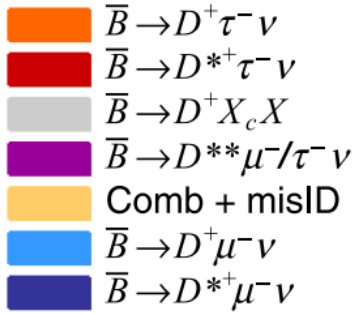
2 fb^{-1} integrated luminosity

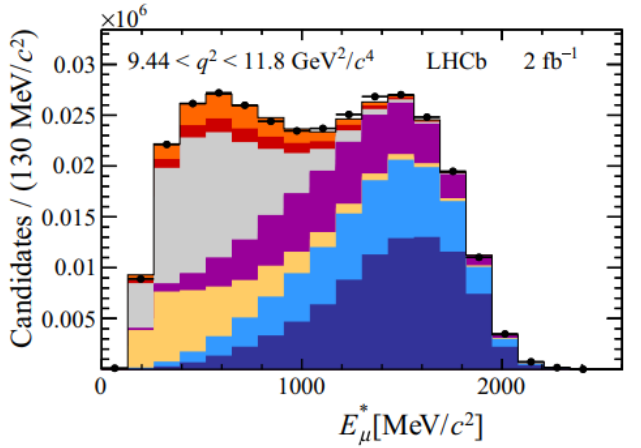
Measure $BF(\overline{B}^0 \to D^{(*)+}\tau^-\overline{\nu}_\tau)/BF(\overline{B}^0 \to D^{(*)+}\mu^-\overline{\nu}_\mu)$

with $D^{*+} \to D^+(\to K^-\pi^+\pi^+)\pi^0$









Determine signal yields using 3-D fit with

$q^2 = (p_{B^0} - p_{D^{(*)}})^2$

$M^2_{miss} = (p_{B^0} - p_{D^{(*)}} - p_\mu)^2$

E^*_μ: muon energy in B rest frame

Where the templates are derived from simulation and control data

$R(D^{*+}) = 0.402 \pm 0.081 \pm 0.085$
$R(D^+) = 0.249 \pm 0.043 \pm 0.047$
Correlation : $\rho = -0.39$

$R(D^{*-})$ with hadronic τ decays

PRD 108 (2023) 012018 Erratum

Data collected in 2015-2016 corresponding to 2 fb^{-1} integrated luminosity

Measure $BF(B^0 \to D^{*-}\tau^+\nu_\tau)$ with $D^{*-} \to \bar{D}^0\pi^-$

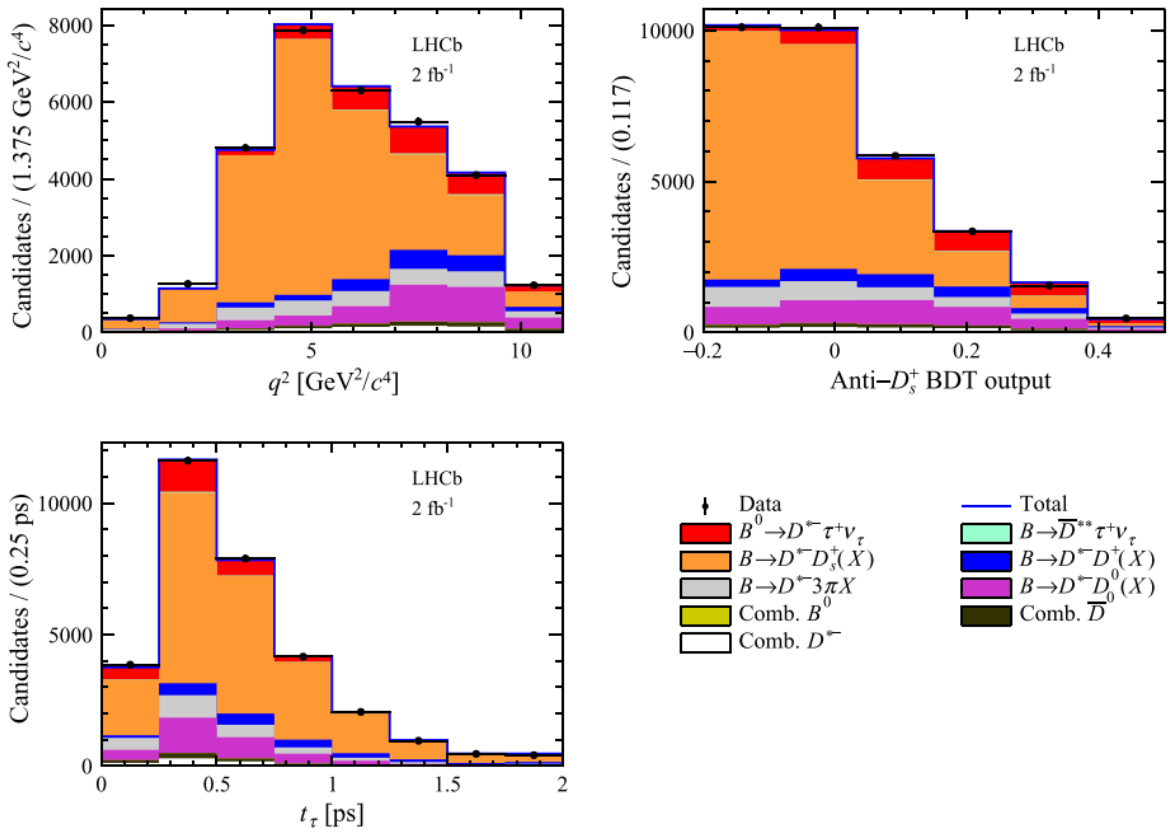
- Using normalization mode $B^0 \to D^{*-}\pi^+\pi^-\pi^+$
- Derive $R(D^{*-})$ using known $BF(B^0 \to D^{*-}\mu^+\nu_\tau)$

Determine signal yields using 3-D fit with

$q^2 = (p_{B^0} - p_{D^{*-}})^2$, Anti-D_s^+ BDT output and τ decay time (t_τ)

Ratio of background $B \to \bar{D}^{**}\tau^+\nu_\tau$ is fixed using PDG value.

Templates are derived from simulation and control data.



$$R(D^{*-}) = 0.260 \pm 0.015 \pm 0.016 \pm 0.012$$
$$R_{comb}\ (D^{*-}) = 0.267 \pm 0.012 \pm 0.015 \pm 0.013$$

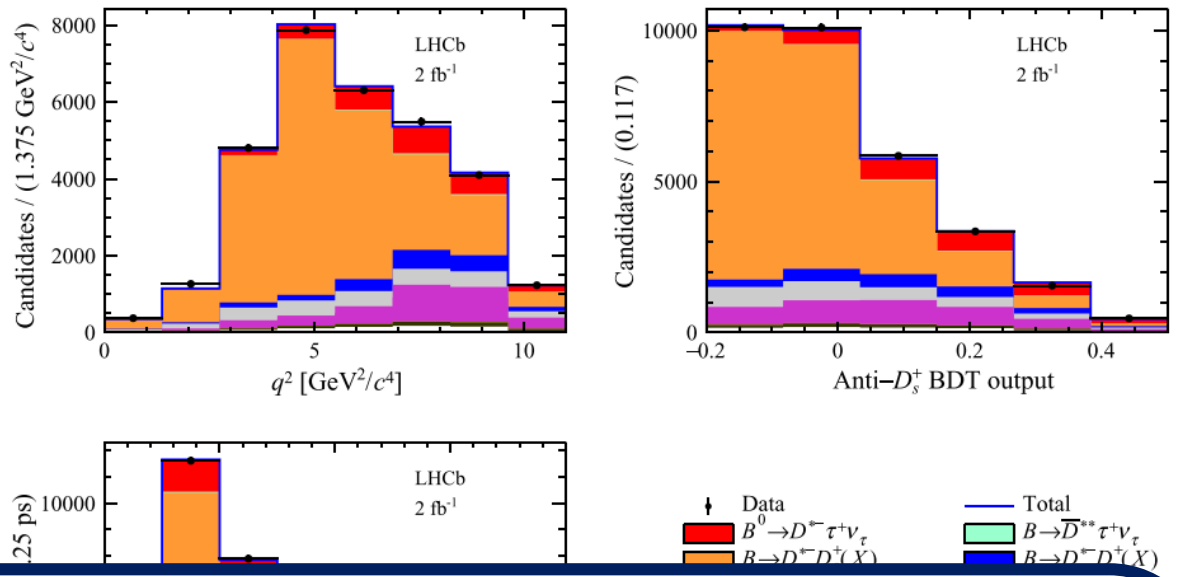
*Combined with previous results

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

$R(D^{*-})$ with hadronic τ decays

PRD 108 (2023) 012018 Erratum

Data collected in 2015-2016 corresponding to 2 fb^{-1} integrated luminosity



Measure $BF(B^0 \to D^{*-}\tau^+\nu_\tau)$ with $D^{*-} \to \bar{D}^0\pi^-$

- Using normalization mode $B^0 \to D^{*-}\pi^+\pi^-\pi^+$
- De

De

q^2 =

Rat

Tem

Both measurements using muonic and hadronic τ decays are compatible with the world average and agree with SM prediction (PRD 107 (2023) 052008) within 1σ

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

Introduction

Goals of the analysis

- Search for $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ with hadronic τ decay

  D^{**0} states in this study

  $D_1'(2400)^0 : m = 2412 \pm 9, \quad \Gamma = 314 \pm 29$

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

  $D_2^*(2460)^0 : m = 2461.1 \pm 0.8, \Gamma = 47.3 \pm 0.8$

  Unit : m [MeV/c^2], Γ [MeV/c]

- Measure $BF\left(B^- \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau\right) \times BF\left(D_{1,2}^{**0} \to D^{*+}\pi^-\right)$

  with normalization channel $B^- \to D_{1,2}^{**0} D_s^{(*)-}$

  where $D_{1,2}^{**0}$ involves $D_1(2420)^0, D_2^*(2460)^0$

- Due to limited knowledge of the $D^*\tau^-\bar{\nu}_\tau$ contamination by $D^{**0}\tau^-\bar{\nu}_\tau$, this measurement is an important input for other $\boldsymbol{R(D^*)}$ **measurements**.

- Measure $R\left(D_{1,2}^{**0}\right) = \frac{BF(B^- \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau)}{BF(B^- \to D_{1,2}^{**0}\mu^-\bar{\nu}_\mu)}$

  SM prediction : 0.09 ± 0.02

  PRD 97 (2018) 075011

Analysis strategy

Dataset : 9 fb^{-1} Run 1 & 2 data

Suppress $B \to D^{**0}\pi^-\pi^-\pi^+(X)$ with **flight distance requirement** on the τ^-

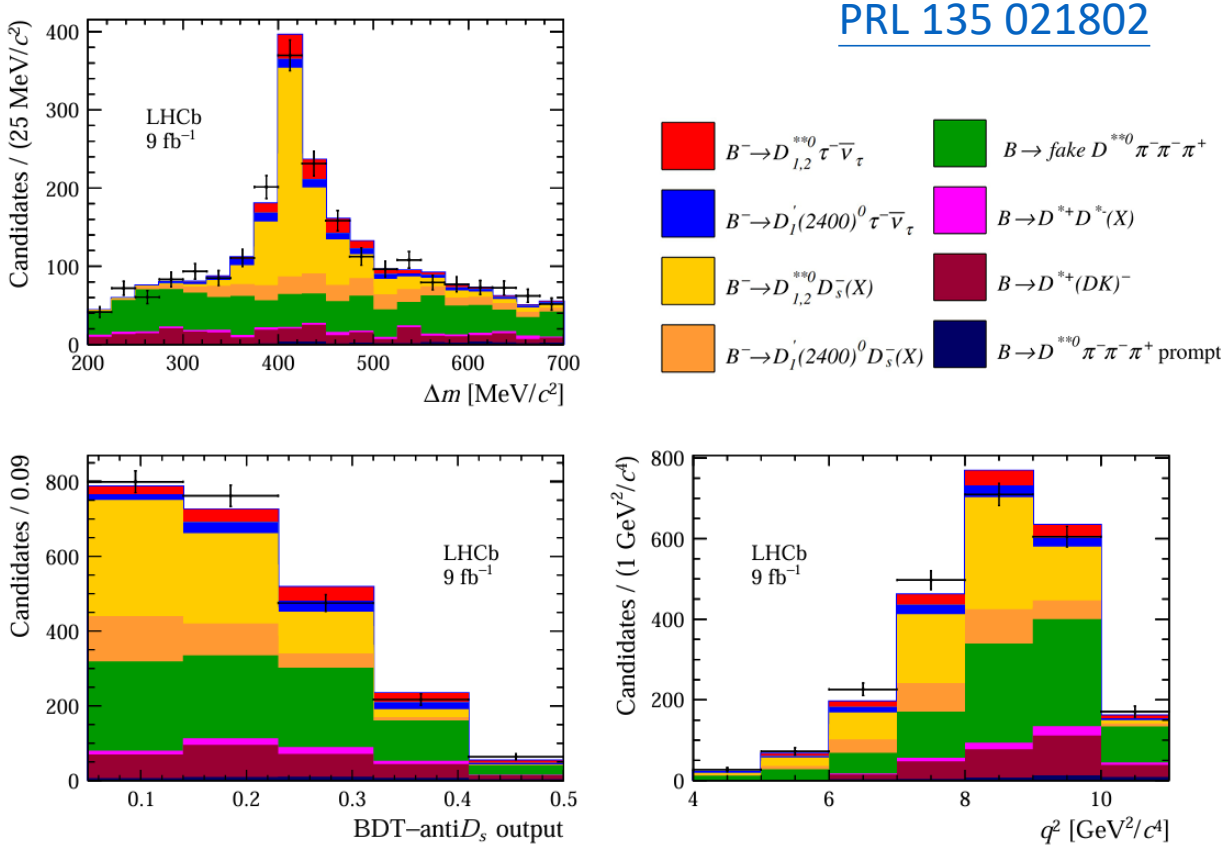
Three multivariate BDTs to reject

- Fake D^{**0} candidates
- Background $D^{**0}_{1,2} \to D^{*+}\pi^-$
  where π^- from 5-prong D_s^+ decay
- $D_s^+ \to \pi^+\pi^-\pi^+(X)$ mimicking hadronic τ^+decay
  (denoted as anti-D_s^+ BDT)

3D Binned fit to extract the yields

- $\Delta m = m_{D^{**0}} - m_{D^{*+}}$
- anti-D_s^+ BDT output
- $q^2 = (p_{B^0} - p_{D^{(*)}})^2 = m^2$ of $\tau^-\bar{\nu}_\tau$ system

PRL 135 021802



123 ± 23 $B^- \to D^{**0}_{1,2}\tau^-\bar{\nu}_\tau$ candidates

220 ± 34 $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ candidates

Results

PRL 135 021802

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

- Pure $D_2(2460)^0$ contribution excluded at 2.7 σ

The branching ratio measurement

- $\frac{BF(B^- \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau)}{BF(B^- \to D_{1,2}^{**0}D_s^{(*)-})} = 0.19 \pm 0.04 \pm 0.02$, with $BF(B^- \to D_{1,2}^{**0}D_s^{(*)-})$ value in PDG Phys. Rev. D 110, 030001 (2024)

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

$$= (0.051 \pm 0.013 \pm 0.006 \pm 0.009)$$

From uncertainty of $BF(B^- \to D_{1,2}^{**0}D_s^{(*)-})$ in PDG

Measured for the first time !

- With known $BF(B^- \to D_{1,2}^{**0}\mu^-\bar{\nu}_\mu)$ value in PDG,

$$R\left(D_{1,2}^{**0}\right) = \frac{BF(B^- \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau)}{BF(B^- \to D_{1,2}^{**0}\mu^-\bar{\nu}_\mu)} = 0.13 \pm 0.03 \pm 0.01 \pm 0.02$$

Measured for the first time !

Agree with SM prediction 0.09 ± 0.02 ! PRD 97 (2018) 075011

Results

PRL 135 021802

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

- Pure $D_2(2460)^0$ contribution excluded at 2.7 σ

The branching ratio measurement

- $\frac{BF(B^-\to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau)}{BF(B^-\to D_{1,2}^{**0}D_s^{(*)-})} = 0.19 \pm 0.04 \pm 0.02$, with $BF(B^- \to D_{1,2}^{**0}D_s^{(*)-})$ value in PDG Phys. Rev. D 110, 030001 (2024)

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

$$= (0.051 \pm 0.013 + 0.006 + 0.009)$$

- With know

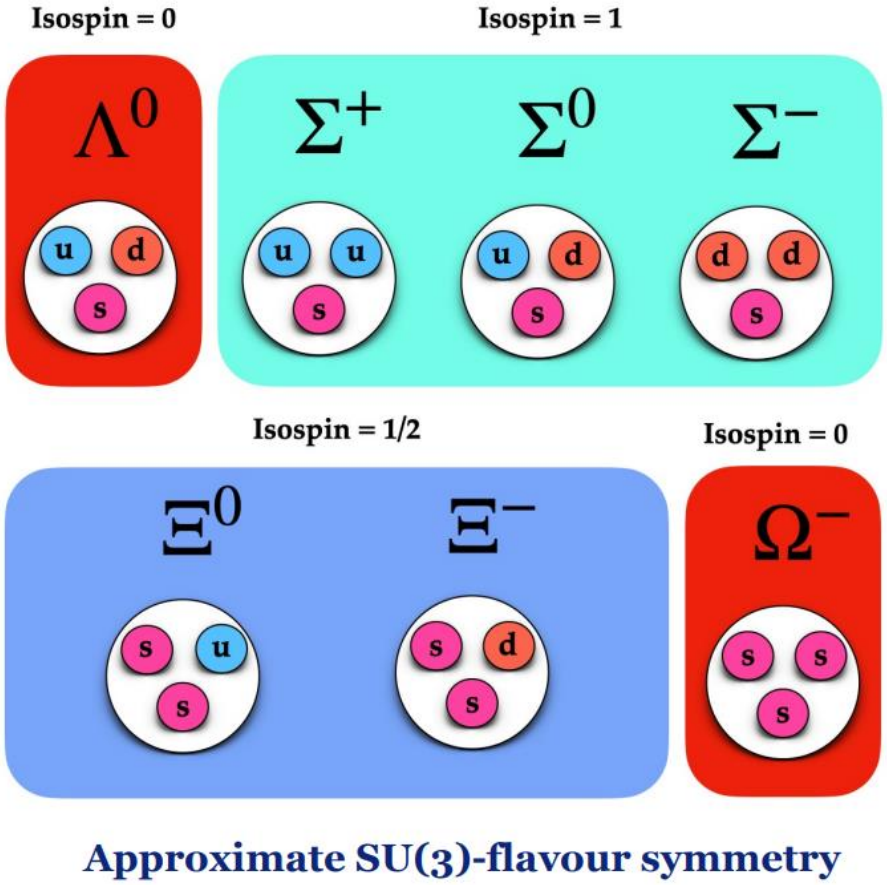
$$R\left(D_{1,2}^{**0}\right) = \frac{BF(B^-\to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau)}{BF(B^-\to D_{1,2}^{**0}\mu^-\bar{\nu}_\mu)}$$

Important input for future measurements !

Agree with SM prediction 0.09 ± 0.02 ! PRD 97 (2018) 075011 JHEP 05 (2022) 29 arxiv:2102.11608

Measurement of $\Lambda \to p\mu^{-}\overline{\nu}_{\mu}$ branching ratio

Semi-leptonic Hyperon Decays



The LFU test observable defined as the ratio between **muon** and **electron** modes

$$R^{\mu e} = \frac{BF(B_1 \to B_2 \mu^- \bar{\nu}_\mu)}{BF(B_1 \to B_2 e^- \bar{\nu}_e)}$$

is **sensitive** to non standard scalar and tensor contributions.

$^*B_{(1,2)}$ indicates hyperon

In the SM, the dependence on the **form factors** is anticipated to simplify when considering the ratio

$$R^{\mu e}_{\mathrm{SM}} = \sqrt{1-\frac{m_\mu^2}{\Delta^2}}\left(1-\frac{9}{2}\frac{m_\mu^2}{\Delta^2}-4\frac{m_\mu^4}{\Delta^4}\right)+\frac{15}{2}\frac{m_\mu^4}{\Delta^4}\operatorname{arctanh}\left(\sqrt{1-\frac{m_\mu^2}{\Delta^2}}\right)$$

where $\Delta = M_{B_1} - M_{B_2}$

PRL 114 161802

Experimental and theoretical status for $R^{\mu e}$

Investigate whether LFU also breaks in charged-current decays of $s \to u$ transition.

The $R^{\mu e}_{exp} = BF(\Lambda \to p\mu^- \bar{\nu}_\mu)/BF(\Lambda \to pe^- \bar{\nu}_e)$ can be evaluated by only measuring $BF(\Lambda \to p\mu^- \bar{\nu}_\mu)$

- Since the electron mode has already been measured very precisely

Value in PDG : $BF(\Lambda \to pe^- \bar{\nu}_e) = (8.34 \pm 0.14) \times 10^{-4}$ Phys. Rev. D 110, 030001 (2024)

- Best branching fraction measurement until now from BESIII (2021):

$$BF(\Lambda \to p\mu^- \bar{\nu}_\mu) = (1.48 \pm 0.21) \times 10^{-4}$$ PRL 127 121802

The experimental result and the theoretical prediction value :

$$R^{\mu e}_{predction} = 0.1880 \pm 0.0083$$ arXiv:2507.09970 [hep-lat]

$$R^{\mu e}_{exp} = 0.178 \pm 0.028$$

Analysis strategy

LHCb-PAPER-2025-030 (in preparation)

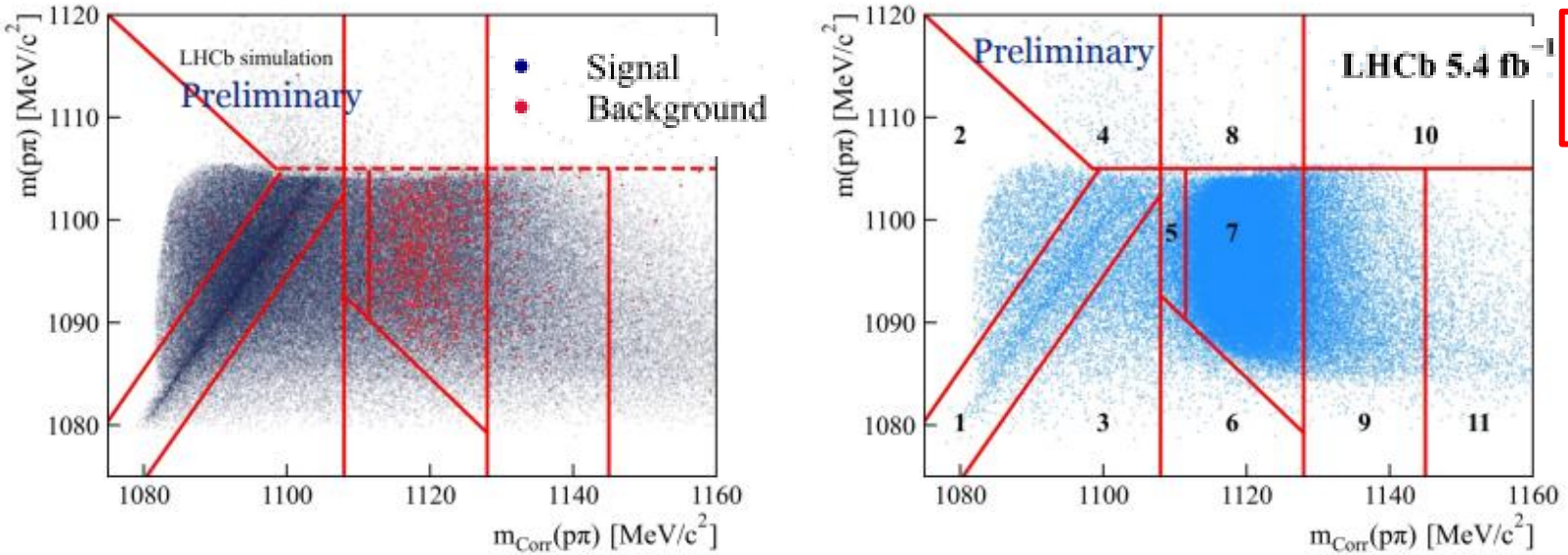
To identify background from $\Lambda \to p\,(\pi^- \to \mu^- \overline{\nu}_\mu)$, kinematic strategies developed for two different scenarios :

-Prompt pion decay (muon at VELO)

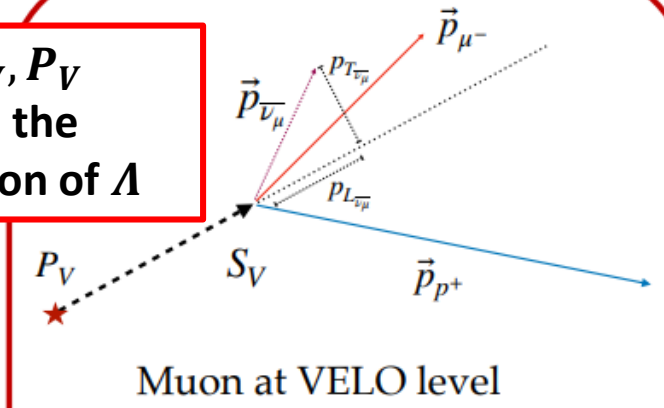
-Late pion decay (pion at VELO)

$m_{corr}(p\pi)$ variable computed using the corrected p_π for distinguishing different components.

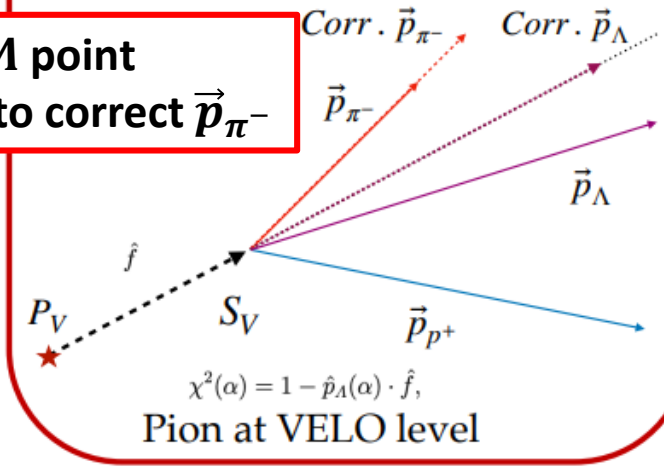
Two-dimensional binned maximum likelihood fit :



Use S_V, P_V to find the direction of Λ



Force Λ point to P_V to correct $\vec{p}_{\pi^-}$



Normalized using $\Lambda \to p\pi^-$ decay to derive the branching ratio

Analysis strategy

LHCb-PAPER-2025-030 (in preparation)

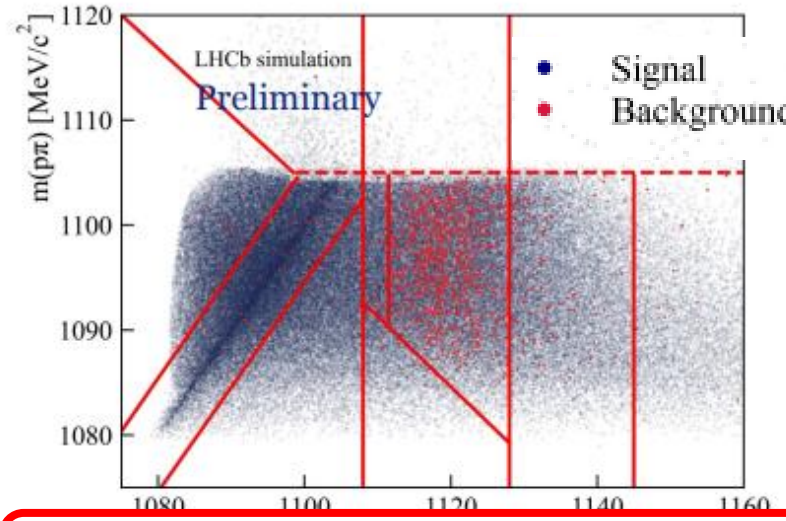
To identify background from $\Lambda \to p\,(\pi^- \to \mu^- \overline{\nu}_\mu)$, kinematic strategies developed for two different scenarios :

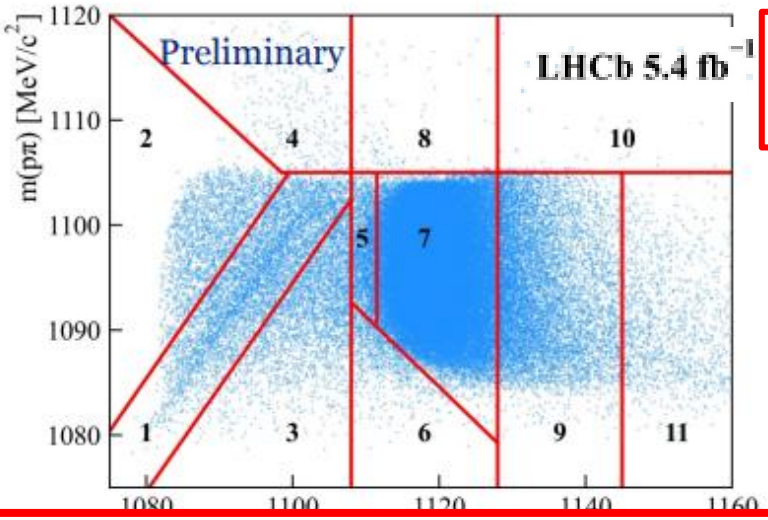
-Prompt pion decay (muon at VELO)

-Late pion decay (pion at VELO)

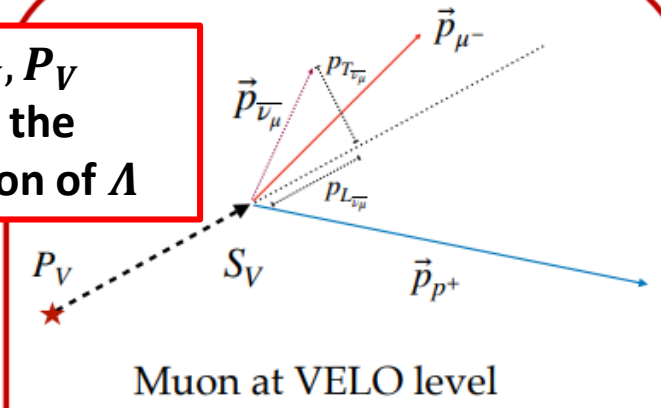
$m_{corr}(p\pi)$ variable computed using the corrected p_π for distinguishing different components.

Two-dimensional binned maximum likelihood fit :

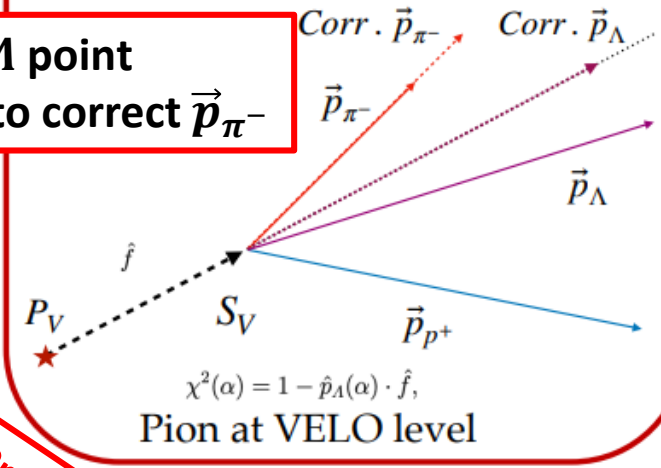




Use S_V, P_V to find the direction of Λ



Force Λ point to P_V to correct $\vec{p}_{\pi^-}$



Preliminary

$$BF\left(\Lambda \to p\mu^-\overline{\nu}_\mu\right) = (1.462 \pm 0.016(\text{stat.}) \pm 0.100(\text{sys.}) \pm 0.011(\text{norm})) \times 10^{-4}$$

Results

LHCb-PAPER-2025-030
(in preparation)

- LHCb has performed the **world best** $BF(\Lambda \to p\mu^-\bar{\nu}_\mu)$ measurement, total uncertainty of 6.9%

  $BF(\Lambda \to p\mu^-\bar{\nu}_\mu) = (1.462 \pm 0.016(\text{stat.}) \pm 0.100(\text{sys.}) \pm 0.011(\text{norm})) \times 10^{-4} = (\mathbf{1.46 \pm 0.10}) \times \mathbf{10^{-4}}$
- The result is in good agreement with BESIII measurement.
- Since there is a long-standing tension in the determination of V_{us}, we indirectly measured V_{us} :

$$V_{us} = 0.253 \pm 0.011$$

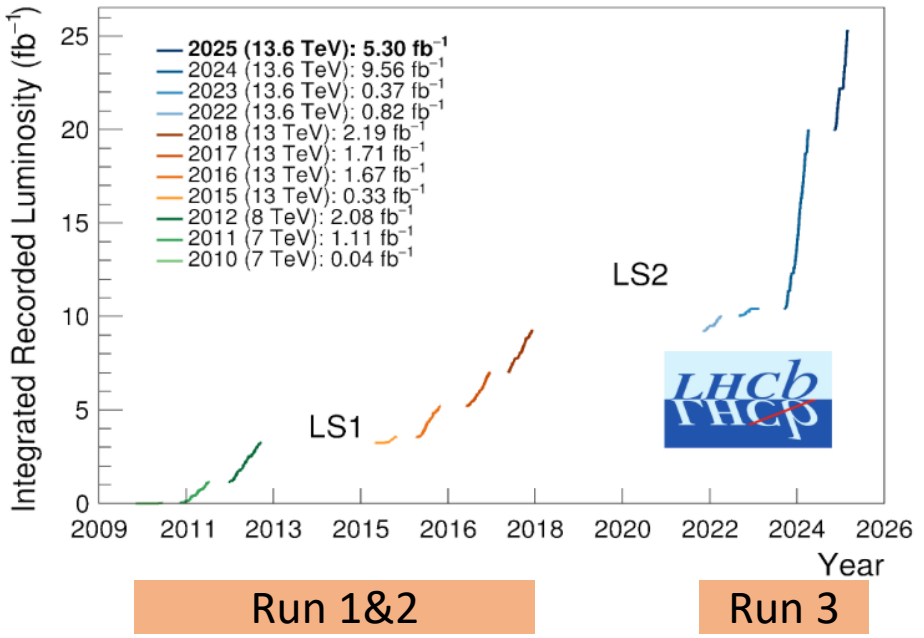
- Uncertainty **very large** compared to the PDG extractions using kaon decays:

$V_{us} = 0.22431 \pm 0.00085$, considered both K_{l3} and $K_{\mu 2}$ results PDG V_{us} 2024

- This measurement implies new constraints in $R^{\mu e}$ (LFU in $s \to u$ transitions).
- The extracted $R^{\mu e} = 0.175 \pm 0.012$ **agrees with the SM prediction**

Conclusion

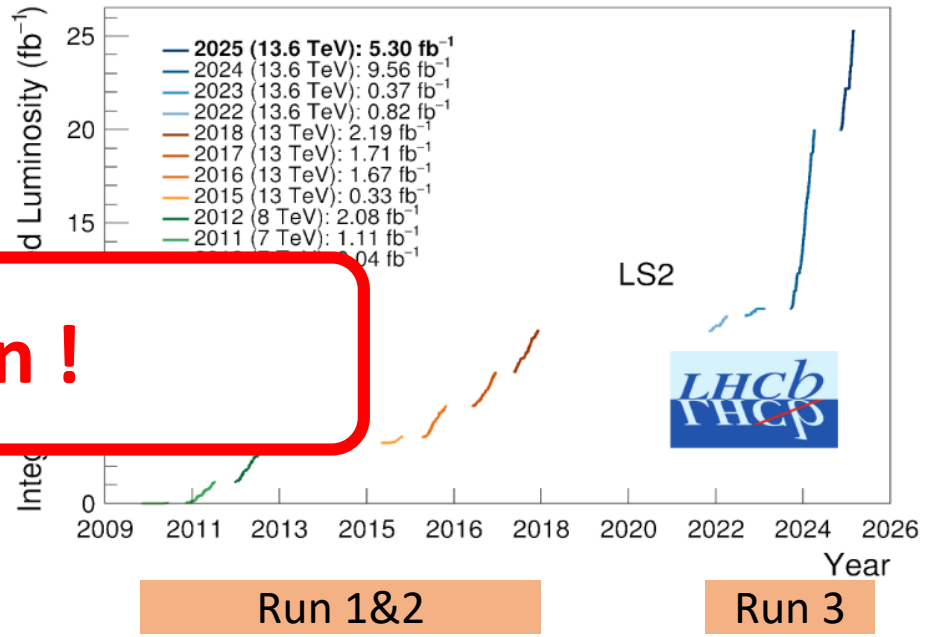
- The **muonic** τ decay $R(D^{(*)+})$ and **hadronic** τ decay $R(D^{*-})$ measurements are **consistent with** the **SM prediction** and **previous measurements**.
- $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decay are observed, the branching ratio of $B^- \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau$ with $D_{1,2}^{**0} \to D^{*+}\pi^-$ and $R\left(D_{1,2}^{**0}\right)$ are measured for **the first time**.
- LHCb has **the best** $BF\left(\Lambda \to p\mu^-\bar{\nu}_\mu\right)$ for now, extracted $R^{\mu e} = 0.175 \pm 0.012$ is **consistent with SM prediction.**
- Several semi-leptonic programs on LFU measurement is ongoing
  - $R(D^{*-})_{\mu/e}$ $R(D_s^*)$ $R(J/\Psi)$ measurements
  - Angular analysis : $\bar{B}^0 \to D^{(*)+}\mu^-\bar{\nu}_\mu$, $\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau$, $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$
- $R(D^{*-})_{\tau/e}$ and angular analyses **using Run 3 data** is under preparation



Conclusion

- The **muonic** τ decay $R(D^{(*)+})$ and **hadronic** τ decay $R(D^{*-})$ measurements are **consistent with** the **SM prediction** and **previous measurements**.
- $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ decay are observed, the branching ratio of $B^- \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau$ with $D_{1,2}^{**0} \to D^{*+}\pi^-$ and $R\left(D_{1,2}^{**0}\right)$ are measured for **the first time**.
- LHCb has **the best** $BF\left(\Lambda \to p\mu^-\bar{\nu}_\mu\right)$ for now, extracted $R^{\mu e} = 0.175 \pm 0.012$ is **consistent with SM prediction.**
- Several semi-leptonic programs on LFU measurement is ongoing
  - $R(D^{*-})_{\mu/e}$ $R($
  - Angular anal
- $R(D^{*-})_{\tau/e}$ and angular analyses **using Run 3 data** is under preparation

Thanks for your attention !



Backup

$R(D^{(*)+})$ with muonic τ decays – control sample

Split the data into four regions with isolation tool

Region 1

- No track is in the vicinity of the signal candidate. Used as **signal region.**

Region 2 & 3

- One or two additional $\pi^{\pm}$ are around the signal candidate. Used for modeling $\overline{B}^0 \to D^{**}\tau^-\overline{\nu}_\tau$ **background.** D^{**} involves

  $D_1(2420), D_2^*(2460), D_1'(2430)$ and $D_0^*(2300)$ for **region 2**

  $D_3(2740), D(3000)^0$ for **region 3**

Region 4

- One additional $K^{\pm}$ is around the signal candidate. Used for modeling $\overline{B} \to D^+(X_c \to \mu^- X)(X')$ **background**

$R(D^{*-})$ with hadronic τ decays – control sample

Control region used in this study

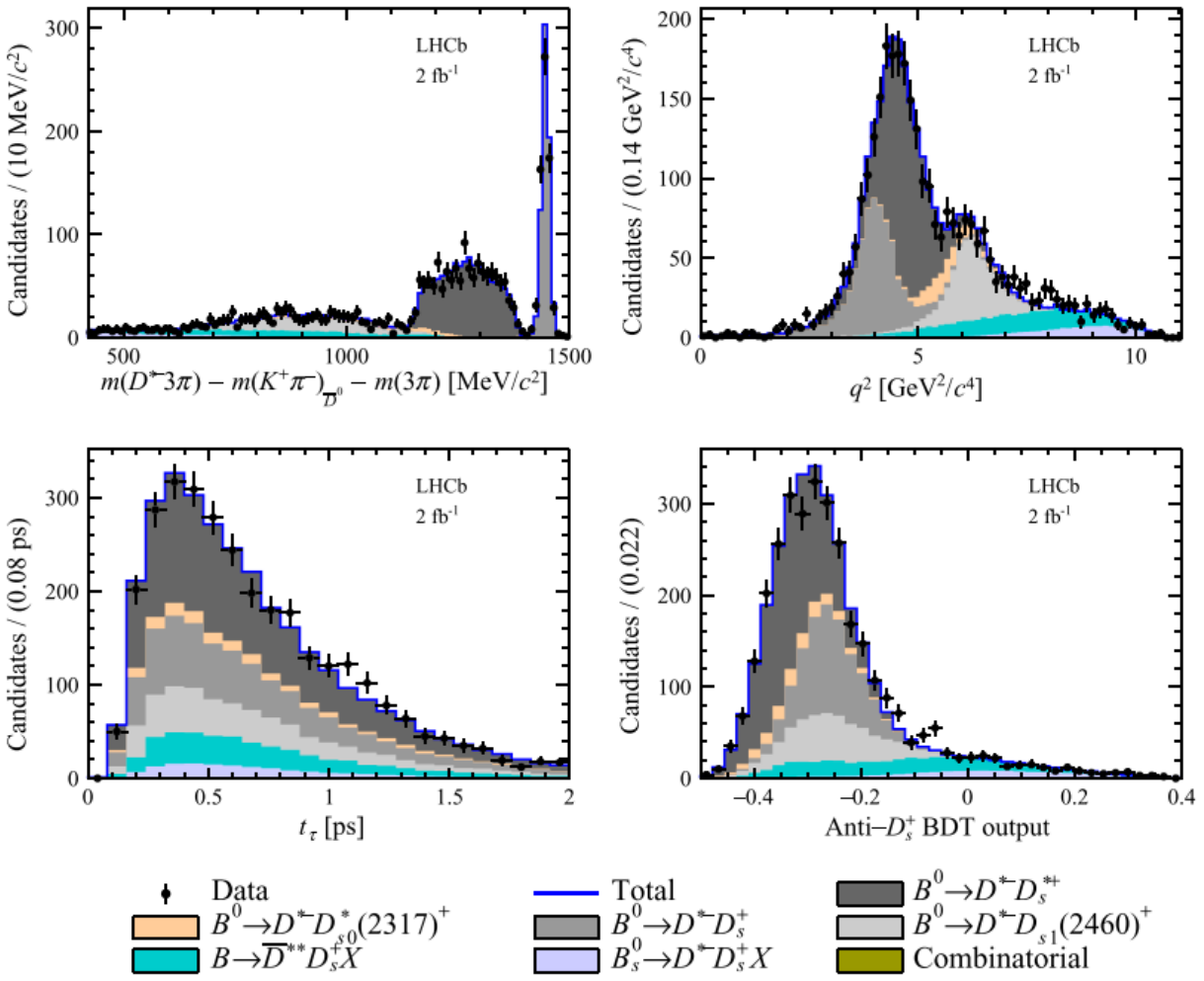
PRD 108 (2023) 012018 Erratum

Region for $B^0 \to D^{*-} D_s^+,\ D_s^+ \to 3\pi X$ background

- Selected with reverse anti-D_s^+ BDT requirement for $B^0 \to D^{*-} D_s^+,\ D_s^+ \to 3\pi X$ background study

Region for $B \to D^{*-} D^0 X$ $B \to D^{*-} D^+ X$ background

- Selected with isolation tool and reverse PID requirement



Background sources in $B^- \to D^{**0}\tau^-\overline{\nu}_\tau$ study

PRL 135 021802

TABLE I. List of the various background categories. The first, second and third columns indicate the decay chain producing each background, the control sample dedicated to its study, and an estimate of its relative contribution in the selected sample, reflected by the number of stars, respectively.

Background source	Control sample	Size
Fake D^{**0}		
Fake D^0 or fake D^{*+}	D^0 and D^{*+} sidebands	*
Genuine D^{*+}; fake D^{**0}	WS sample	***
	$B \to D^{*+}D^{*-}(X)$	*
	$B \to D^{*+}(DK)^-(X)$	**
Genuine D^{**0}		
$B \to D^{**0}\pi^-\pi^-\pi^+X$	$B^- \to D^{**0}\pi^-\pi^-\pi^+$	*
$B^- \to D^{**0}D_s^-(X)$	$B^- \to D^{*+}D_s^-(\to \pi^-\pi^-\pi^+)(X)$	***
$B^- \to D^{**0}(DK)^-$	$B \to D^{*+}D^0(\to K^-\pi^+\pi^+\pi^-)(X)$	Negligible

Selections of $B^- \to D^{**0}\tau^-\overline{\nu}_\tau$

Dataset : 9 fb^{-1} Run 1 & 2 data

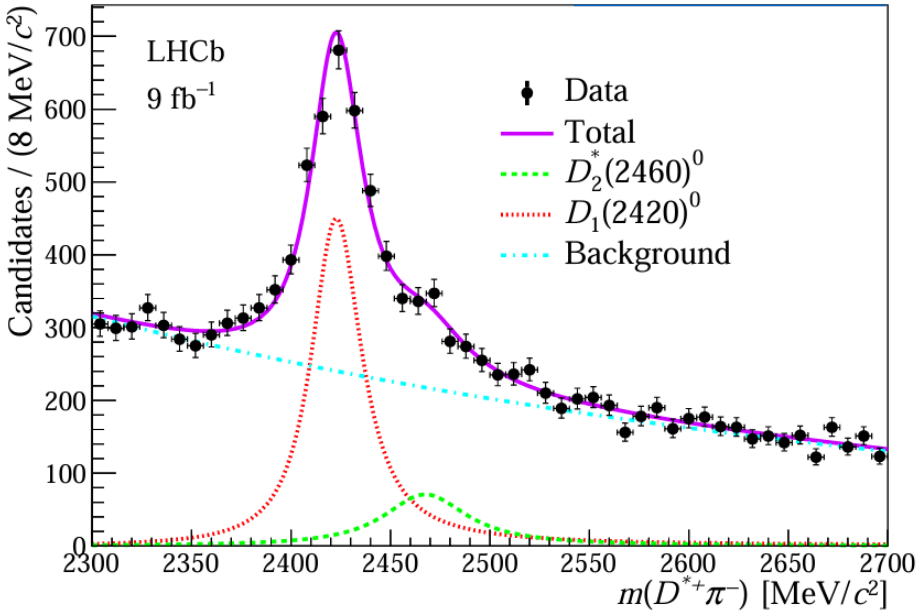
Select signal with

- Trigger and pre-selection requirements
- Flight distance requirement on the τ^- for $B \to D^{**0}\pi^-\pi^-\pi^+(X)$ suppression

Three multivariate BDTs to reject

- Fake D^{**0} candidates
- Background $D^{**0}_{1,2} \to D^{*+}\pi^-$ where π^- from 5-prong D_s^+ decay
- $D_s^+ \to \pi^+\pi^-\pi^+(X)$ mimicking hadronic τ^+decay (denoted as anti-D_s^+ BDT)

PRL 135 021802



Mass distribution of $D^{**0} \to D^{*+}\pi^-$ in data after **all the selections**. To have more statistics for better investigation, the plot is fit without anti-D_s^+ BDT requirements.

Signal yield extraction

PRL 135 021802

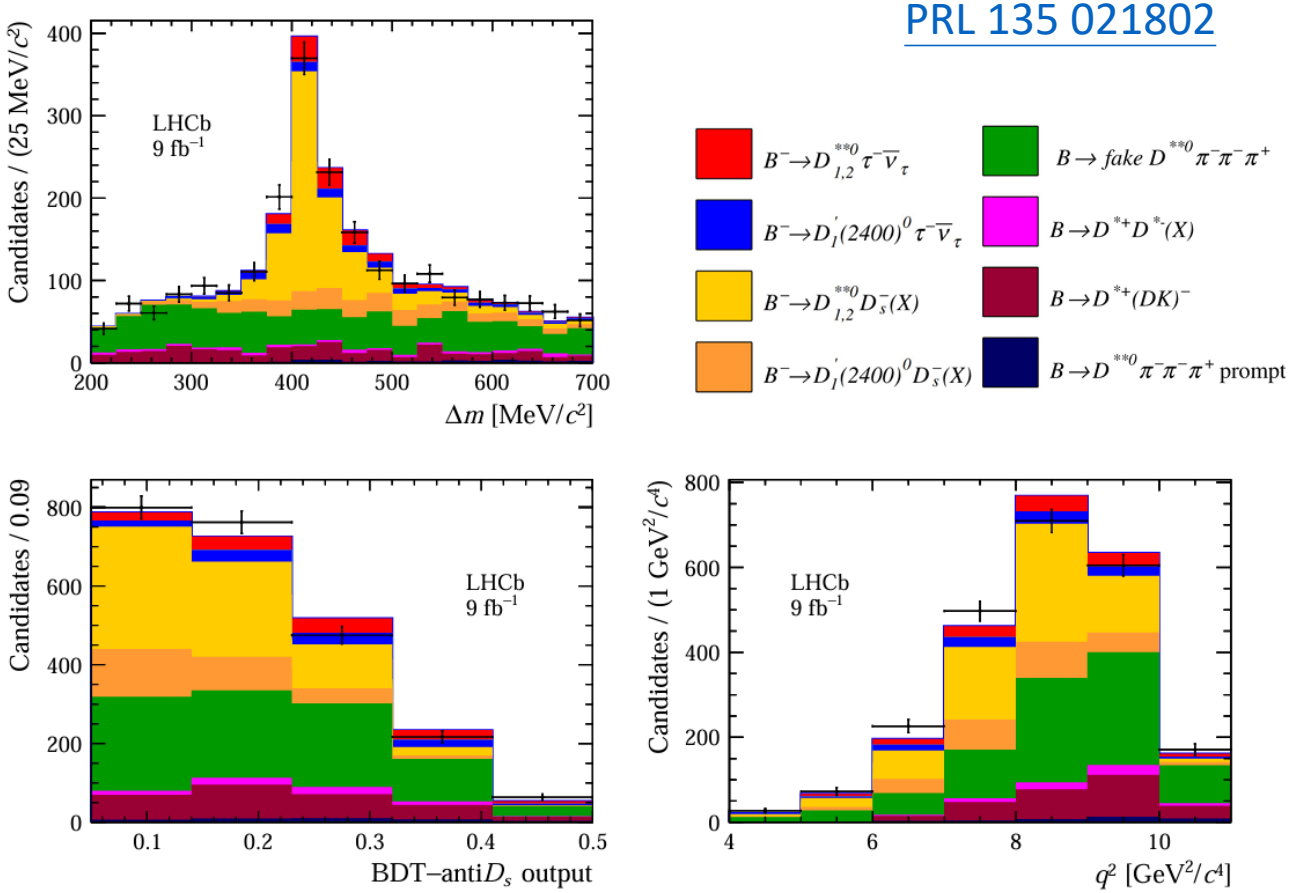
3D Binned fit to extract the yields

- $\Delta m = m_{D^{**0}} - m_{D^{*+}}$
- anti-D_s^+ BDT output
- $q^2 = (p_{B^0} - p_{D^{(*)}})^2$ = m^2 of $\tau^- \bar{\nu}_\tau$ system

Signal templates from simulation

- Combined $D_1(2420)^0$ and $D_2^*(2460)^0$ template
- Relative size of $D_1(2420)^0$, $D_1'(2400)^0$ and $D_2^*(2460)^0$ are fixed in simulation.

Backgrounds templates from simulation and control samples



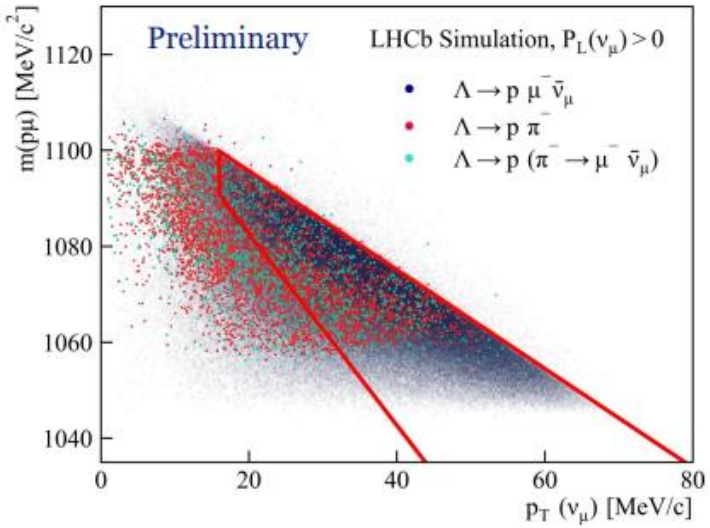
123 ± 23 $B^- \to D_{1,2}^{**0}\tau^-\bar{\nu}_\tau$ candidates

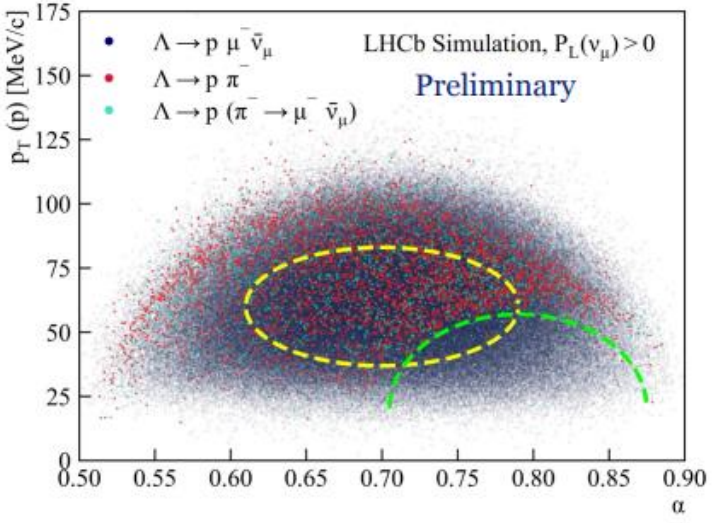
220 ± 34 $B^- \to D^{**0}\tau^-\bar{\nu}_\tau$ candidates

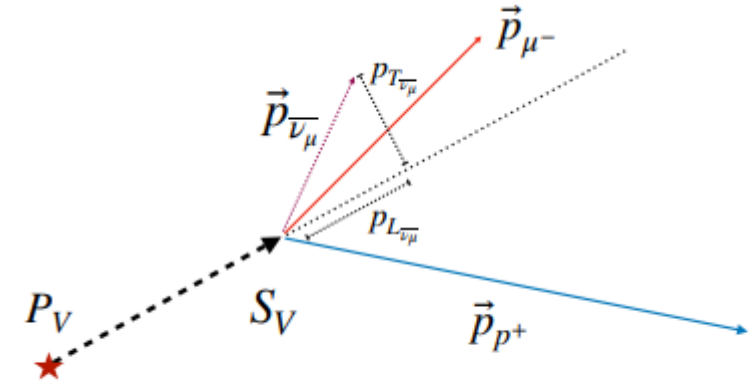
Signal selection of $\Lambda \to p\mu^-\overline{\nu}_\mu$ study

LHCb-PAPER-2025-030 (in preparation)

Select signal based on kinematic variables:



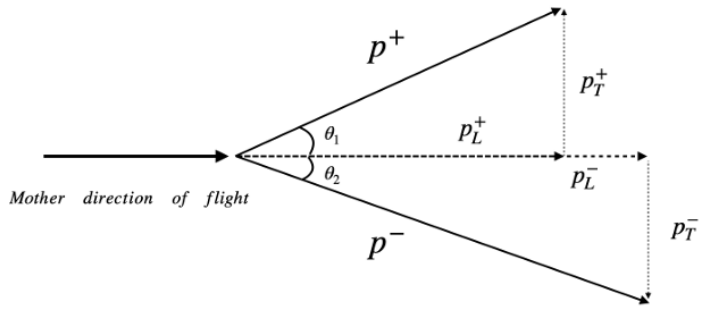




Muon at VELO level

Derive $\vec{p}_{\overline{\nu}_\mu}$ using Λ flight direction, $\vec{p}_{\mu^-}$, $\vec{p}_p$ and m_Λ

Where $\alpha = \dfrac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$



$p^+ : p \; or \; \pi^+$
$p^- : \bar{p} \; or \; \pi^-$

Systematic uncertainties in $\Lambda \to p\mu^-\overline{\nu}_\mu$ study

LHCb-PAPER-2025-030 (in preparation)

Source	Relative Uncertainty (%)
$\mathcal{B}(\Lambda \to p\pi^-)$	0.78 %
Correction TISTISTIS Effs.	3.0 %
Correction Tracking Effs.	1.6 %
Correction PID Effs.	3.5 %
NormLine Fit	expected to be negligible
Binning PidCalib SignalLine	1.61 %
Binning PidCalib NormLine	1.04 %
Intrinsic Tracking Uncertainty	1.8 %
$\Lambda \to p\mu^-\overline{\nu}_\mu$ yield (fit binning)	3.9 %
Signal fit template	expected to be negligible
MC TruthMatch	0.69 %