Measurement of the $\bar{B} \to D^{**\circ}\tau^-\bar{\nu}_\tau$ decay rate

Guy Wormser

IJCLab Orsay

on behalf of the LHCb Collaboration

Chanllenge in Semileptonic decays, Vienna, September 24, 2024

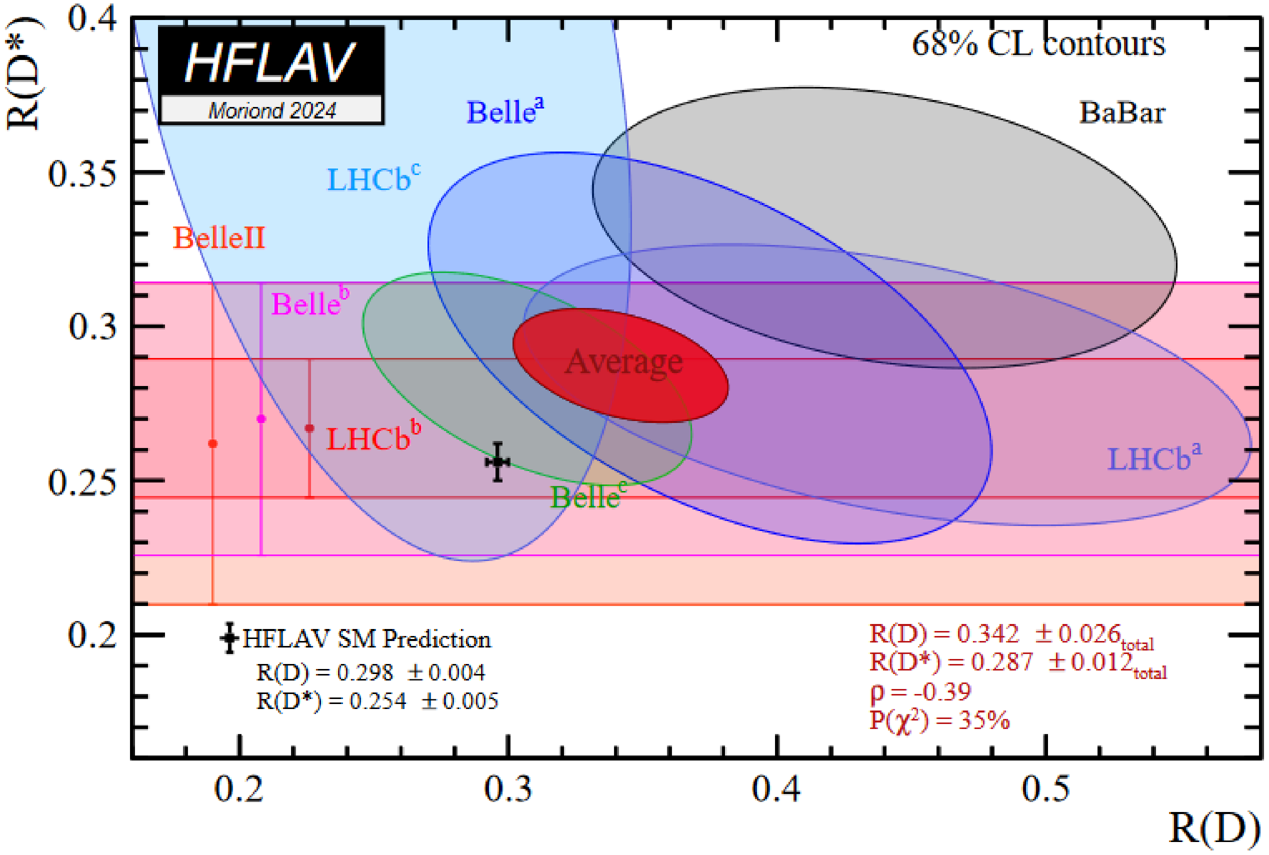
R(D*) and D** feed-down

Ever since the first R(D)-R(D*) measurement 12 years ago, **the possibility that the observed excess is due to D** feed-down** has been mentioned

B ➔ $D^{**}\tau\nu$; D** ➔D(*)X

B can be B° or B^+; D**can be D**° or D** $^+$

This is a common systematics to all R(D $^{(*)}$) measurements in all experiments



Present discrepancy with SM : 3.3 σ

The D** family

- $D_1(2420)$ $\frac{1}{2}(1^+)$
- $D_2^*(2460)$ $\frac{1}{2}(2^+)$
- $D_1'(2430)$ $\frac{1}{2}(1^+)$
- $D_0^*(2400)$ $\frac{1}{2}(0^+)$

The $D_0(2400)$ does not decay to D*

D_1 and D_2* are narrow states

Theoretical predictions in RMP

Florian U. Bernlochner, Manuel Franco Sevilla, Dean J. Robinson, and Guy Wormser, Rev. Mod. Phys. 94, 015003

$$\mathcal{R}(D_0^*) = 0.08(3), \qquad \mathcal{R}(D_1') = 0.05(2),$$
$$\mathcal{R}(D_1) = 0.10(2), \qquad \mathcal{R}(D_2^*) = 0.07(1)\,.$$

- **These ratios give BR(B→D**τν)/BR(B → D** μν) . Typically BR(B→D**μν) is 10% BR(B→D*μν)**
- **In addition, these R ratios need to be multiplied by BR(D**→D*π)**

The visible BR(B->Dτν) are therefore expected to be ~0.02-0.03 %**

Parent	Final State $D^*\pi^+$	$D^*\pi^0$	$D\pi^+$	$D\pi^0$	$\sum D\pi\pi$
D_2^*	0.26	0.13	0.40	0.20	—
D_1	0.42	0.21	—	—	0.36
D_1'	0.67	0.33	—	—	—
D_0	—	—	0.67	0.33	—

Recent review of D** feed-down recipes in

Florian U. Bernlochner, Manuel Franco Sevilla, Dean J. Robinson, and Guy Wormser, Rev. Mod. Phys. 94, 015003

- R(D**) assumptions for feed-down subtraction :
  - BABAR 0.18
  - BELLE ~0.15
  - LHCb –muonic : 0.12
  - LHCb-hadronic –Run1 : Sum is 11% of $D^*\tau\nu$ yield
  - LHb-Hadronic Run2 : uses the mentioned theoretical predictions

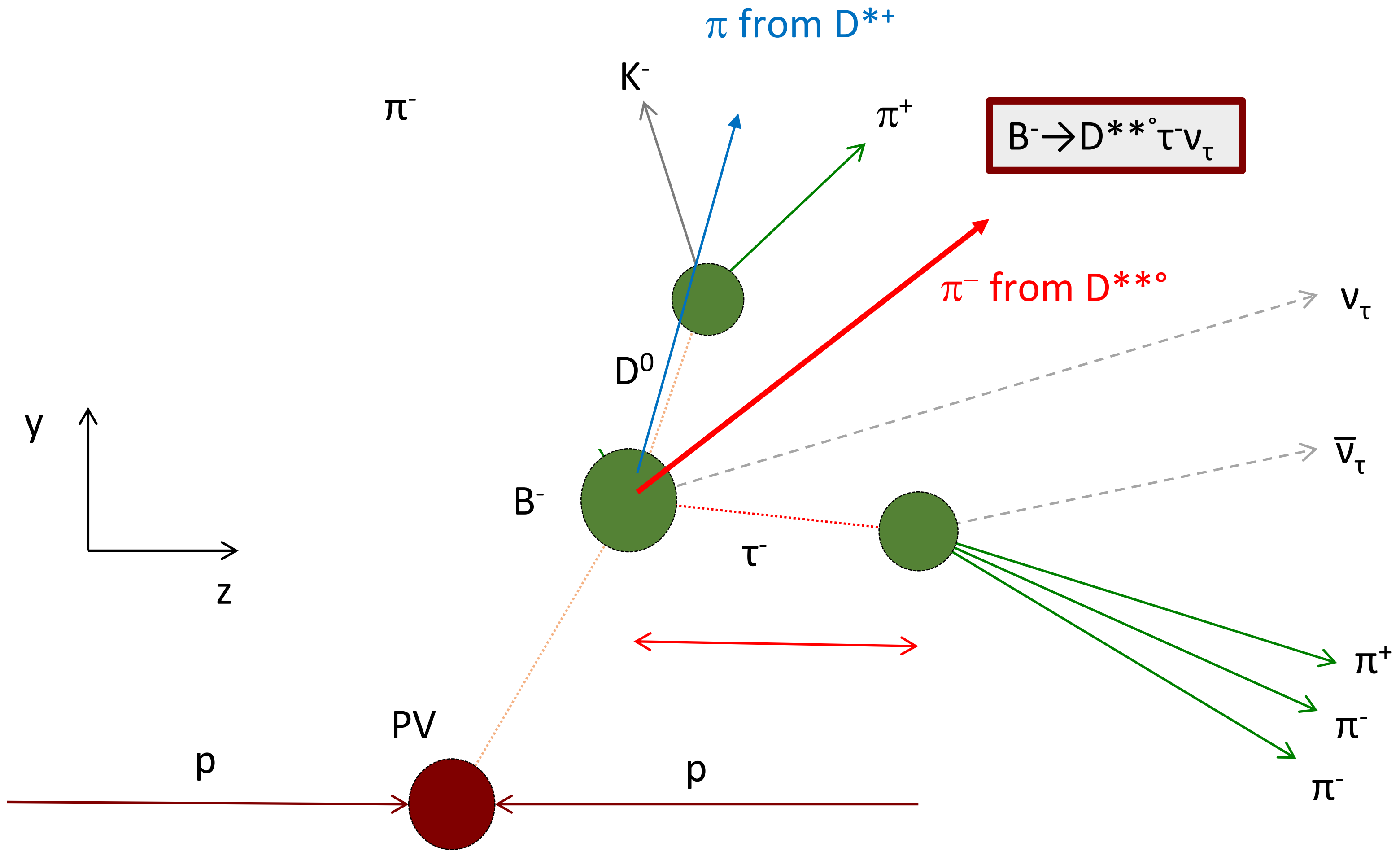
- **ALL experiments allow for a 50% systematic uncertainty of this subtraction**
- **But they are all way above the theoretical predictions, hence potentially minimizing R(D*) discrepancy wrt SM prediction by ~0.5 σ**

Conclusion

- It is quite important to try to consolidate the R(D**) predictions by measurements !!
- Two approaches are being used :
  - Gather as many measurements as possible of the B➔D**W* system with W* decaying into $\mu\nu$, π, $D_{s,}$ a_1 , … and compare with the various theoretical models (e.g. **arxiv hep-ph 2012.11608)**
    - The first three channels are being studied by LHCb !! The fourth one can be done also (ancillary result of this analysis)
      - π : LHCb-PAPER-2016-026
      - D_s : LHCb-PAPER-2024-001 (JHEP08(2024) 165)
      - $\mu\nu$: ongoing effort
  - Try to measure at least one R(D**) ratio : the goal of this analysis

Goal and strategy

- Dual goal:
  - Measure $R(D_1(2420)°)$ per se to confront with SM prediction
  - Measure feed-down from $D^{**}\tau\nu$ decays into $R(D^{*+})$ measurements
- General strategy
  - Starting point : $D^*\tau\nu$ candidates, **with τ reconstructed in the $\pi\pi\pi$ final state**
  - Reconstruct $D^{**}°$ states in the $D^{*+}\pi^-$ final state by adding an extra track to the D* candidate compatible with the B vertex
  - Separate the 3 D** states from the mass spectrum (and angular distributions)
  - Background description from the **data-driven WS sign sample $D^{*+}\pi^+$**
  - **Measure the $D^{**}°\tau\nu$ yield with same analysis flow as R(D*) (LHCb-PAPER-2022-051)**
  - Assume isospin invariance and deduce D^{**+} feed-down in R(D*) analysis


π from D^{*+}
K^-
π^-
π^+
$B^- \rightarrow D^{**\circ} \tau^- \nu_\tau$
π^- from $D^{**\circ}$
ν_τ
D^0
y
$\bar{\nu}_\tau$
B^-
z
τ^-
π^+
π^-
PV
p
p
π^-

Selection

- Key requirement require 1 extra track at the D* vertex which is tagged as the only extra track at the B° vertex
- This track is not one of the 6 tracks forming the $D^*\tau\nu$ candidate. It is a pion (no kaon, no electron)
  - D° to $K3\pi$ could be a source of background
- No Ghost track, no cloned slow pion
- The track is not compatible with the tau vertex (5-prong D_s decay is a large source of background extra-tracks)

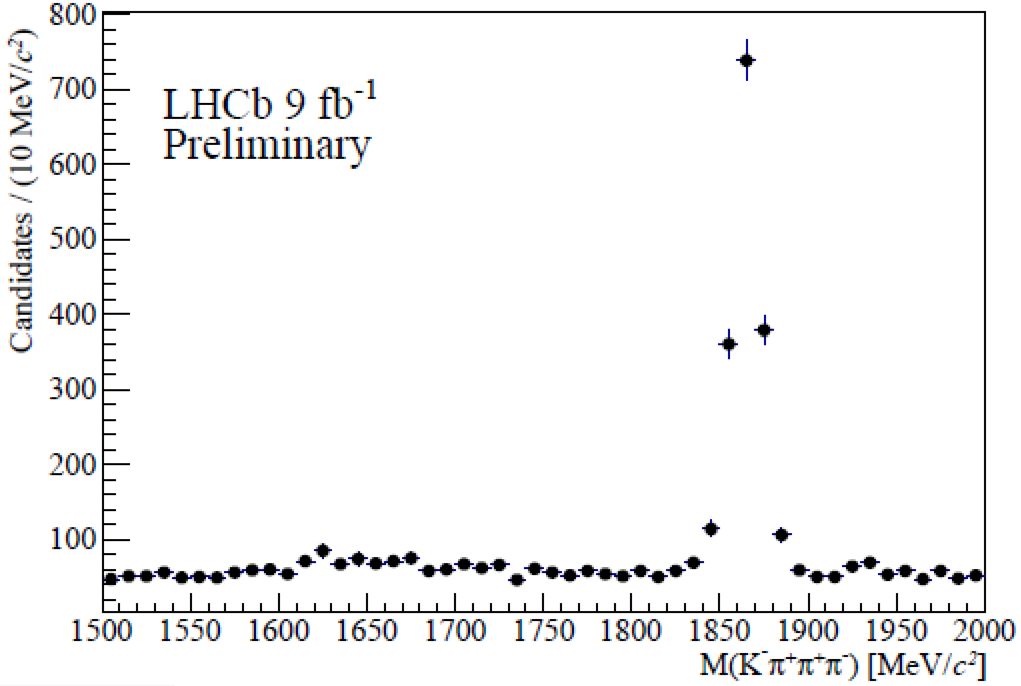
Physics background sources

- True D** events (peaking in the $D^{*+}\pi^-$ mass distribution)
  - D**Ds$^{(,*,**)}$
  - D**3pi prompt background
  - Is there any D**DK background : the answer turned out to be NO (severe lack of phase space)

- Fake D** from a true D* combined with an extra pion
  - Random extra pion
  - Extra pion from physics :
    - D*+D*-, Extratrack from the B vertex
    - D*+Ds;Ds->5 prongs, Extratrack from the tau vertex
    - D*D°K/π Extratrack from the B vertex
    - D*DK/D->4 or 5 prongs Extratrack from the D° vertex
    - etc

Search for D**DK background : Study of D*πD°X events

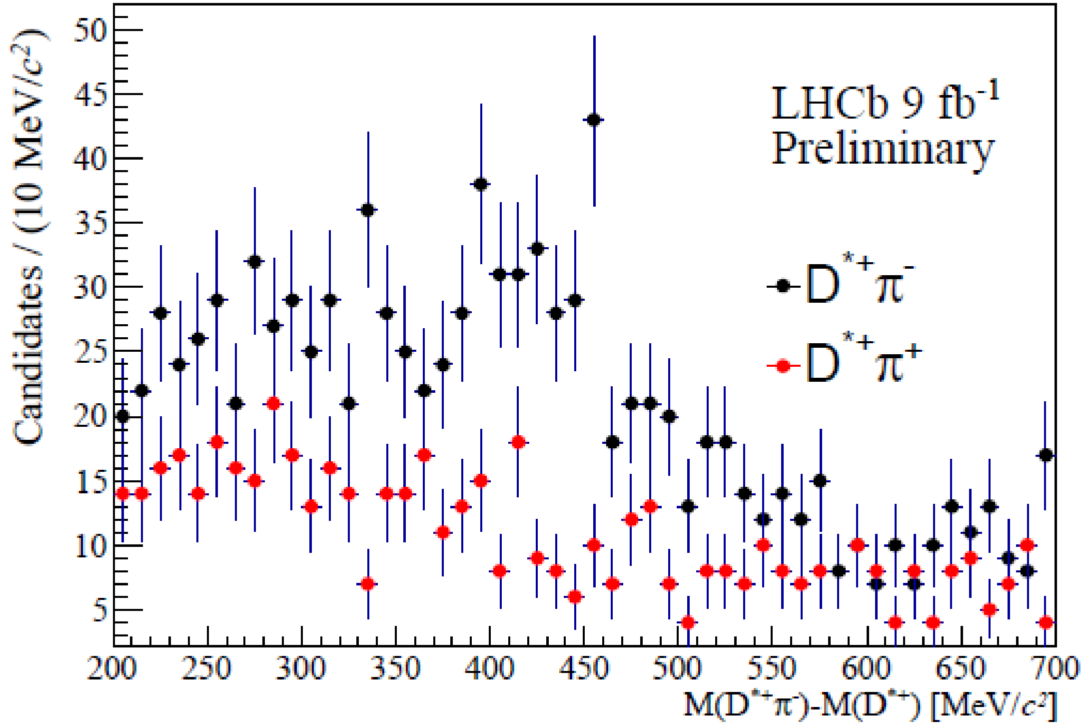
- The isoPlusVtx package can be used to consider one pion extra-track at the B/D* vertex together with one Kaon extra-track at the 3π vertex



LHCb-PAPER-2024-037

Estimate of the D**DX component

LHCb-PAPER-2024-037



Δm distribution with a fully reconstructed D°

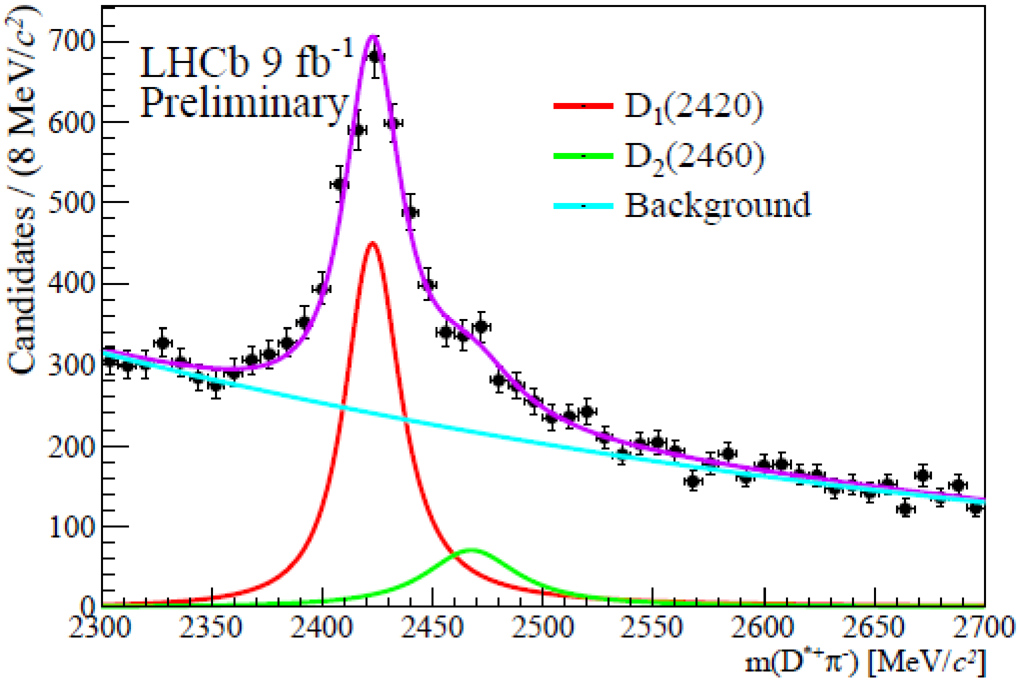
To compute the number of potential D**D°X in the fit sample, consider D*D°X exclusive in the MC (6k) and in the fit sample (720)

The **D**D°X is less than 6 events in the fit sample**

Black RS
Red WS

Inclusive DeltaM peak after vetoing reconstructed D*D° and D*D* events

LHCb-PAPER-2024-037



Preliminary

Yields : D_1 2456±75

D_2 633±69

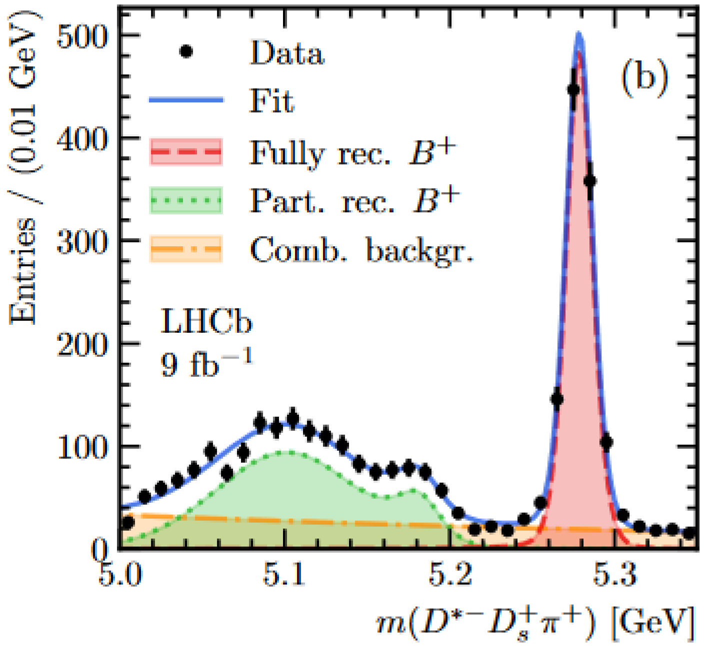
$B^- \rightarrow D^{**} D_s^-$ is chosen as the normalisation channel

- Same underlying physics, same vertex topology, same final state when the D_s^- is reconstructed in the $\pi^-\pi^-\pi^+$ final state
- Amplitude analysis for the decay $B^- \rightarrow D^{*+}\pi^- D_s^-$ recently published by LCHb (LHCb-PAPER-2024-001, JHEP08(2024) 165), using the D_s^- to $KK\pi$ mode
- In this publication, the various D** contributions are measured as well as the BR($B^- \rightarrow D^{*+}\pi^- D_s^{*-}$)
- In this analysis, we build a control sample by reconstructing the D_s^- in the $\pi^-\pi^-\pi^+$ final state

$$\mathcal{R} = \frac{\mathcal{B}(B^+ \to D^{*-} D_s^+ \pi^+)}{\mathcal{B}(B^0 \to D^{*-} D_s^+)} = 0.173 \pm 0.006 \pm 0.008,$$

$$\mathcal{R}^* = \frac{\mathcal{B}(B^+ \to D^{*-} D_s^{*+} \pi^+)}{\mathcal{B}(B^+ \to D^{*-} D_s^+ \pi^+)} = 1.31 \pm 0.07 \pm 0.08.$$

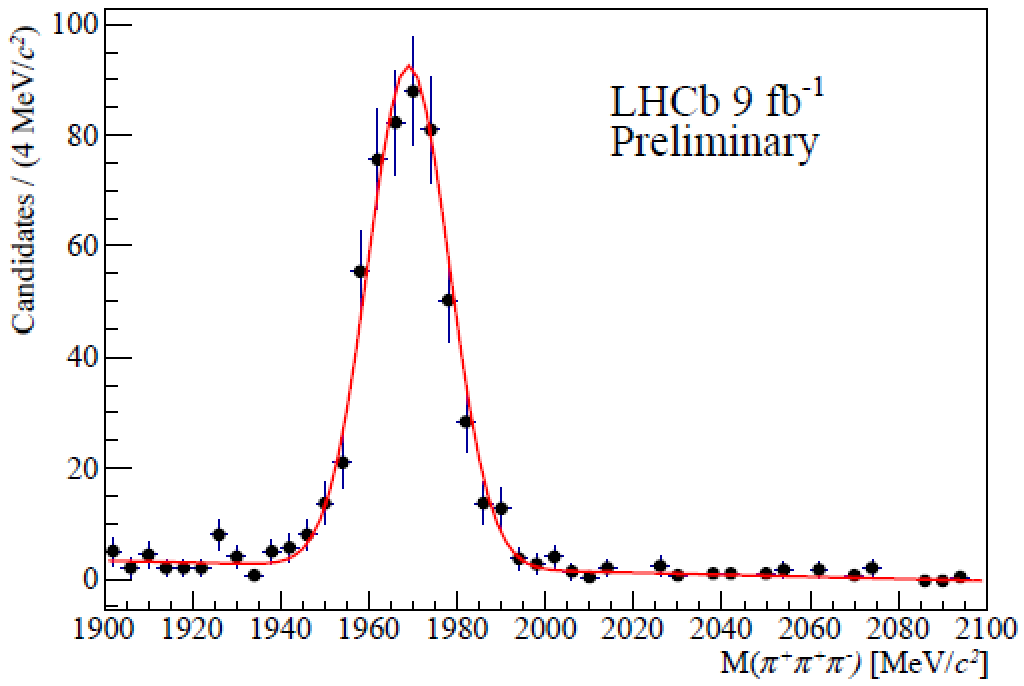
LHCb-PAPER-2024-001



Component	Fit fraction (%)
$D_1(2420)$ S-wave	$3.8 \pm 1.7 \pm 0.8^{+1.3}_{-0.1}$
$D_1(2420)$ D-wave	$71.0 \pm 4.4 \pm 4.6^{+0.0}_{-6.0}$
$D_1(2430)$ S-wave	$14.2 \pm 2.5 \pm 2.4^{+3.1}_{-2.0}$
$D_1(2430)$ D-wave	$0.5 \pm 0.9 \pm 1.5^{+0.2}_{-0.5}$
$D_2^*(2460)$	$11.7 \pm 1.4 \pm 0.8^{+0.0}_{-0.7}$
$D_0(2550)$	$2.3 \pm 0.8 \pm 0.7^{+0.3}_{-1.7}$
$D_1^*(2600)$	$4.8 \pm 1.0 \pm 0.9^{+1.1}_{-2.0}$
$D_2(2740)$ P-wave	$0.4 \pm 0.4 \pm 0.2^{+0.1}_{-0.1}$
$D_2(2740)$ F-wave	$2.3 \pm 0.7 \pm 0.9^{+0.4}_{-0.1}$

$D_s^- \to \pi^-\pi^-\pi^+$ control sample associated to a $D^{**\circ}$ candidate (521 ±12 events)

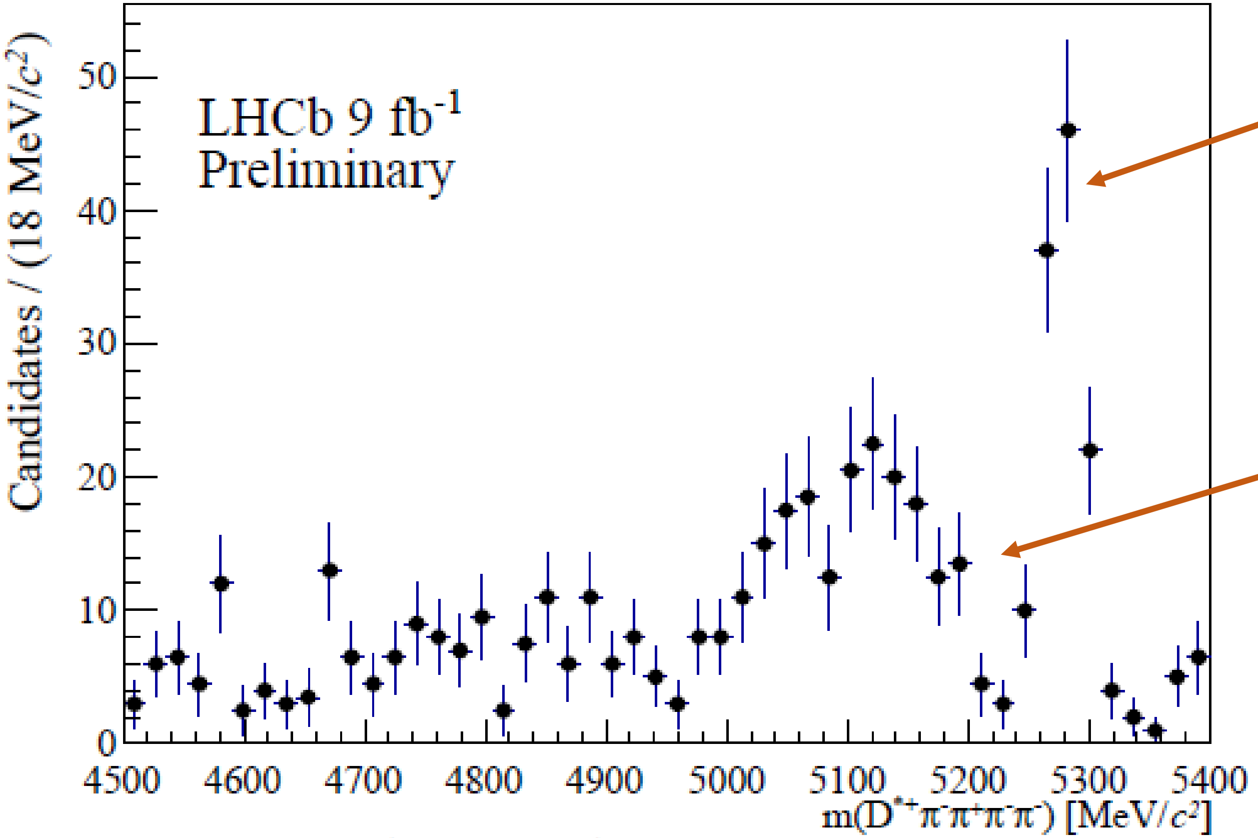
LHCb-PAPER-2024-037



D**3π mass distribution for events with 3π mass in the D_s peak and after sideband subtraction of the Δm peak

LHCb-PAPER-2024-037

Clear separation of D_s, D_s* and D_s** domains



$B^- \to D^{**\circ} D_s^-$

$B^- \to D^{**\circ} D_s^{*-}$

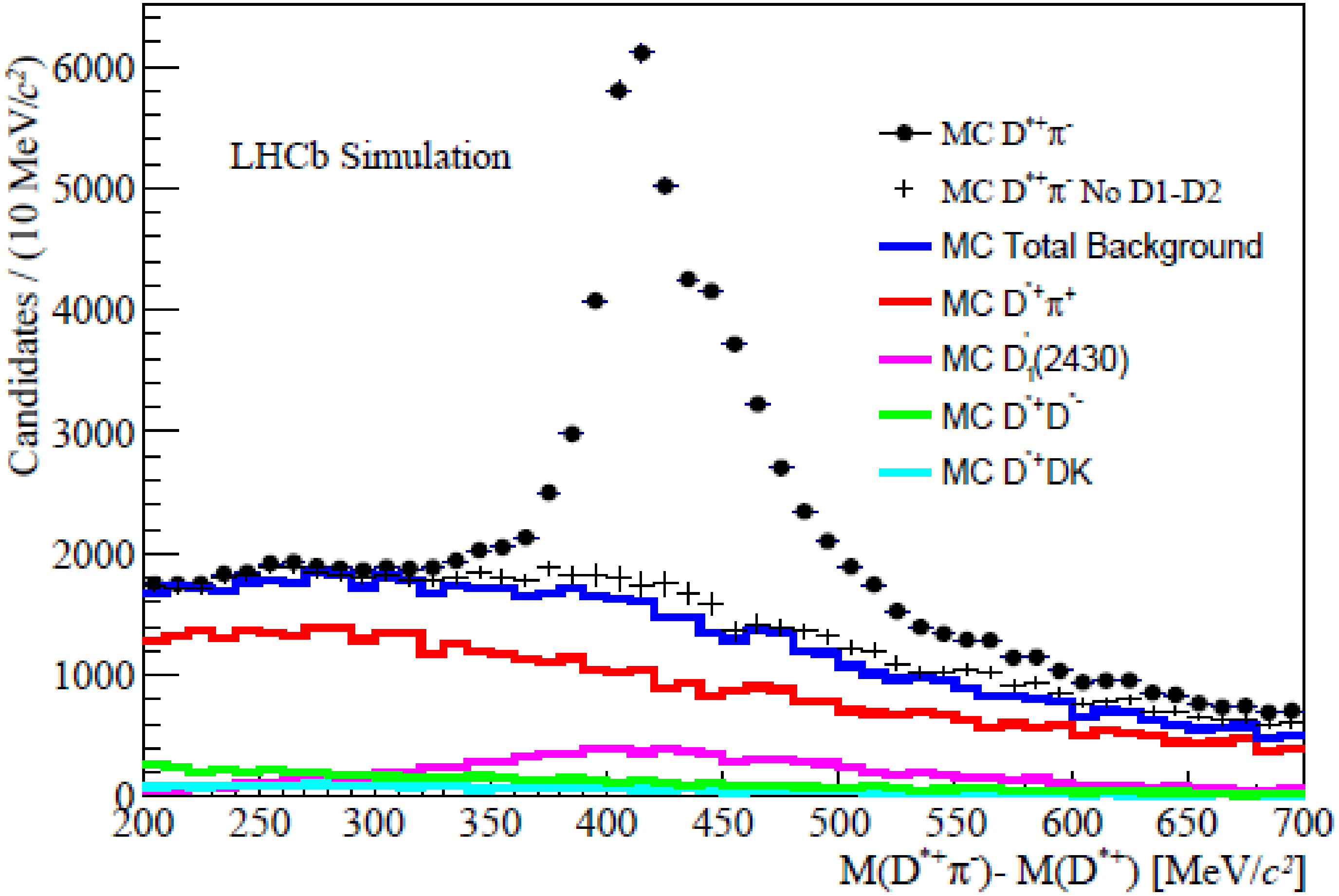
Binned LikelihoodTemplate fit for signal extraction

- 2 $D^{**}\tau\nu$: D_1 and D_2 templates are lumped together
- 7 $D^{**}D_s$ templates
  - D_1 D_s, $D_s{}^*$
  - D_2 D_s $D_s{}^*$
  - D'_1 D_s, $D_s{}^*$
  - D^{**} $D_s{}^{**}$
- $D^{**}3\pi$ prompt sample
- $D^{*+}\pi^+$ WS sample
- 2 extra samples which are not covered by WS : $D^{*+}D^{*-}(X)$, $D^{*-}DK^+/\pi^+$

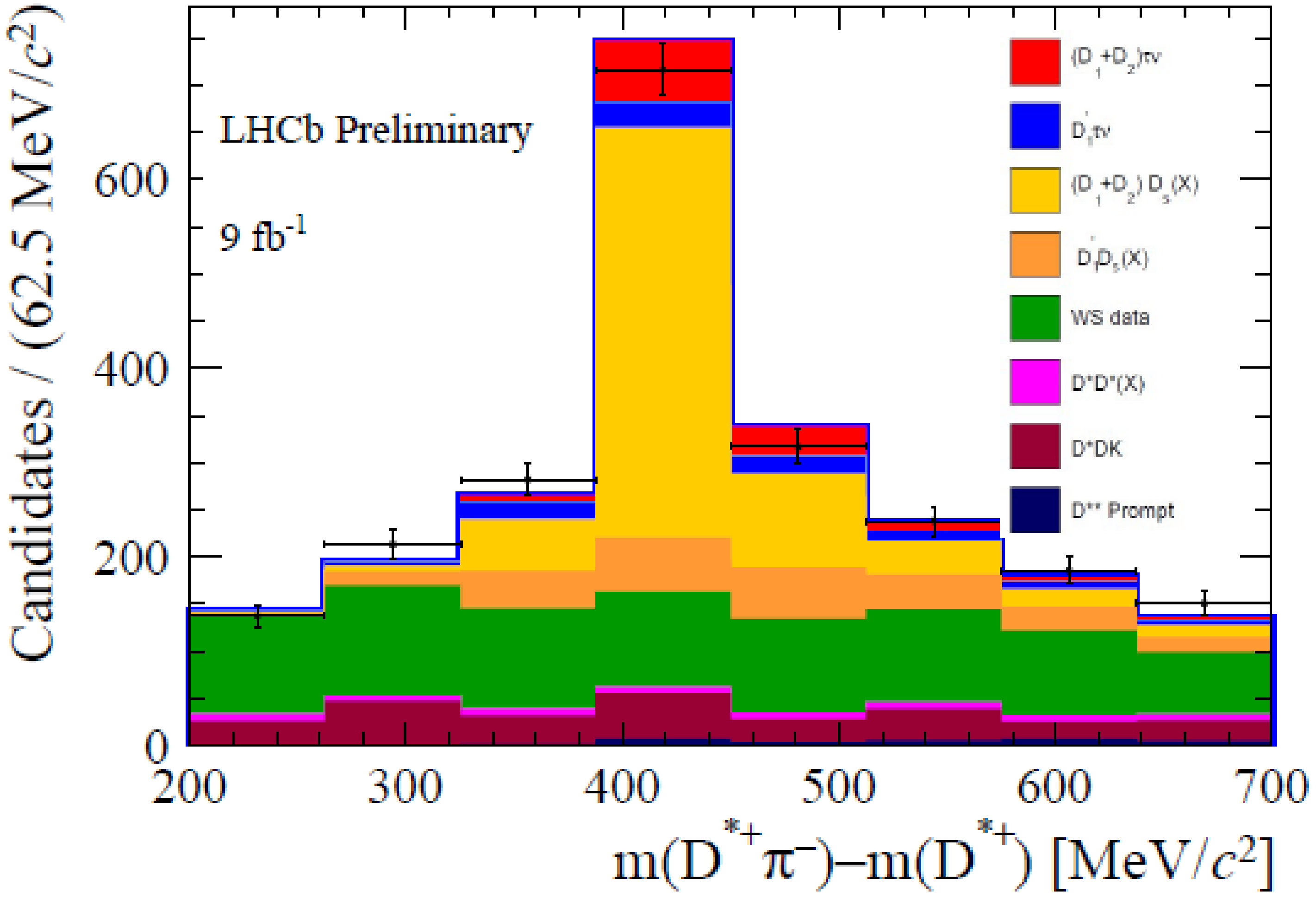
The D*$^{+}\pi^{+}$ background can be used to describe the fake D** background

It must be complemented by contributions producing only RS combinations : B ➔ D*D*(X) and B°➔D*(DK)$^{-}$

LHCb-PAPER-2024-037



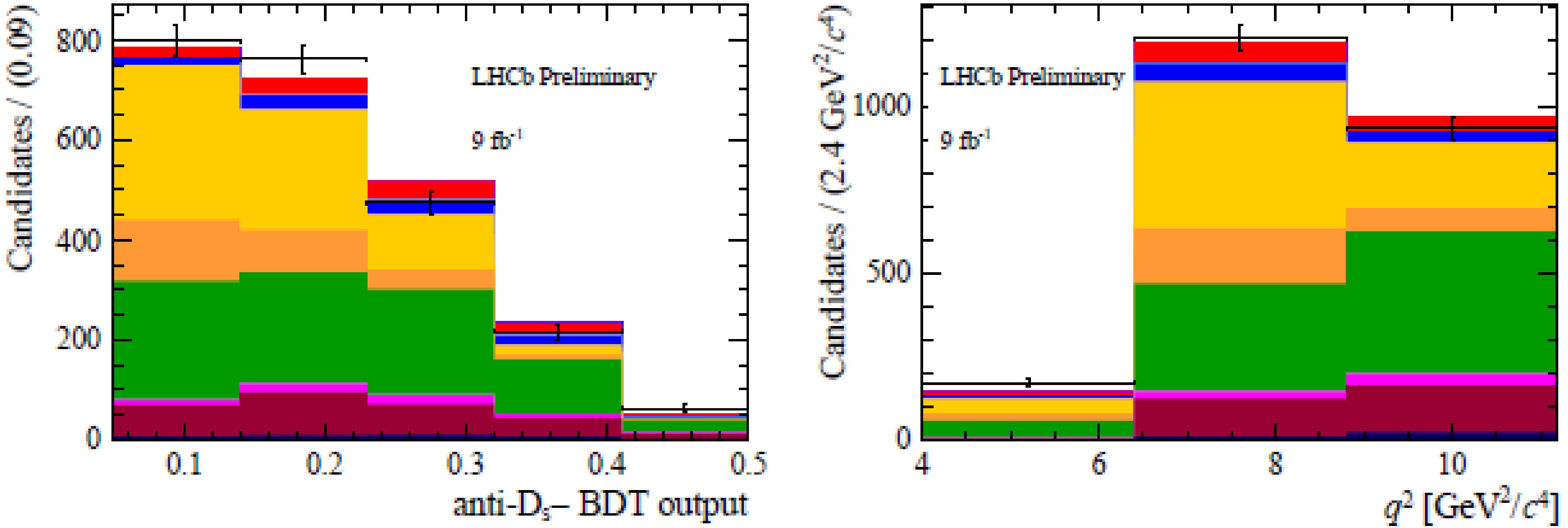
Fit variables : ΔM, q^2, antiD$_s$_BDT



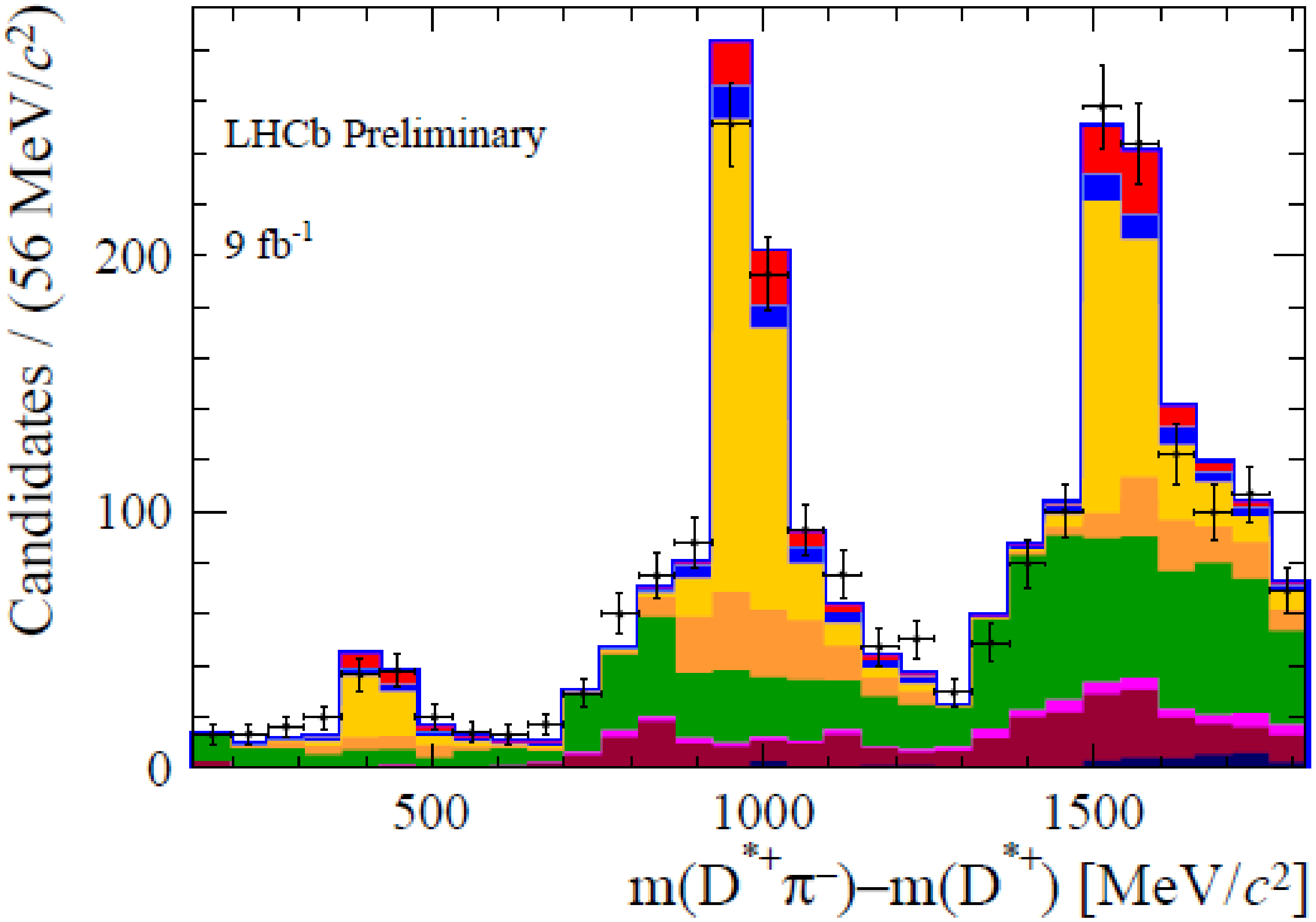
LHCb-PAPER-2024-037

Fit of good quality : χ^2/ndof = 0.89

LHCb-PAPER-2024-037

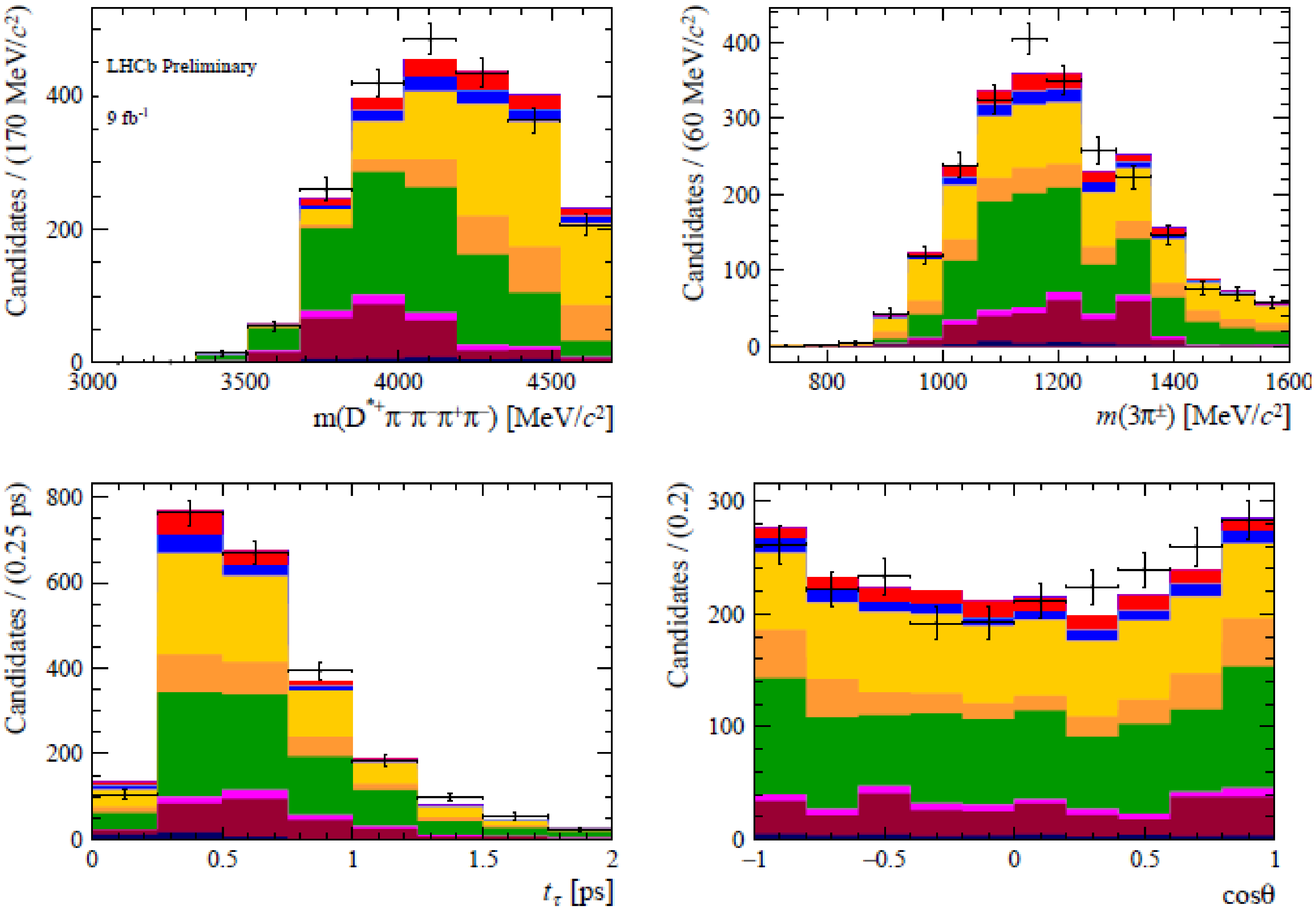


Projection not included in the fit: Δm_q^2



LHCb-PAPER-2024-037

Projections for variables not included in the fit: $D^*3\pi$ mass, 3π mass, τ_τ, $\cos\theta$



LHCb-PAPER-2024-037

Fit results using for fit variables Δm, q^2, BDT

LHCb-PAPER-2024-037

Preliminary

Fit Parameter	Yield
$(D_1^0(2420) + D_2^{*0}(2460))\tau\nu$	122.6±23.2
$D_1^{\prime 0}(2400)\tau\nu$	96.7±24.9
$D_1^0(2420) D_s^{*+}$	317.1±19.2
$D_1(2420) D_s^+$	235.4±15.9
$D_2^{*0}(2460) D_s^+$	39.0±3.1
$D_2^{*0}(2460) D_s^{*+}$	48.1±12.4
$D^{**} D_s^{**+}$	31.5±30.3
$D_1^{\prime 0}(2400) D_s^{*+}$	140.7±28.1
$D_1^{\prime 0}(2400) D_s^+$	112.5±17.1
D^{**} WrongSign	8793.8±73.7
D^{**} Prompt	34.6±7.0
$D^{*-} D^{*+}$ (X)	51.4±55.3
Extra K	248.3±48.4

Evidence of the decay $B^- \to D^{**\circ}\tau^-\nu_\tau$

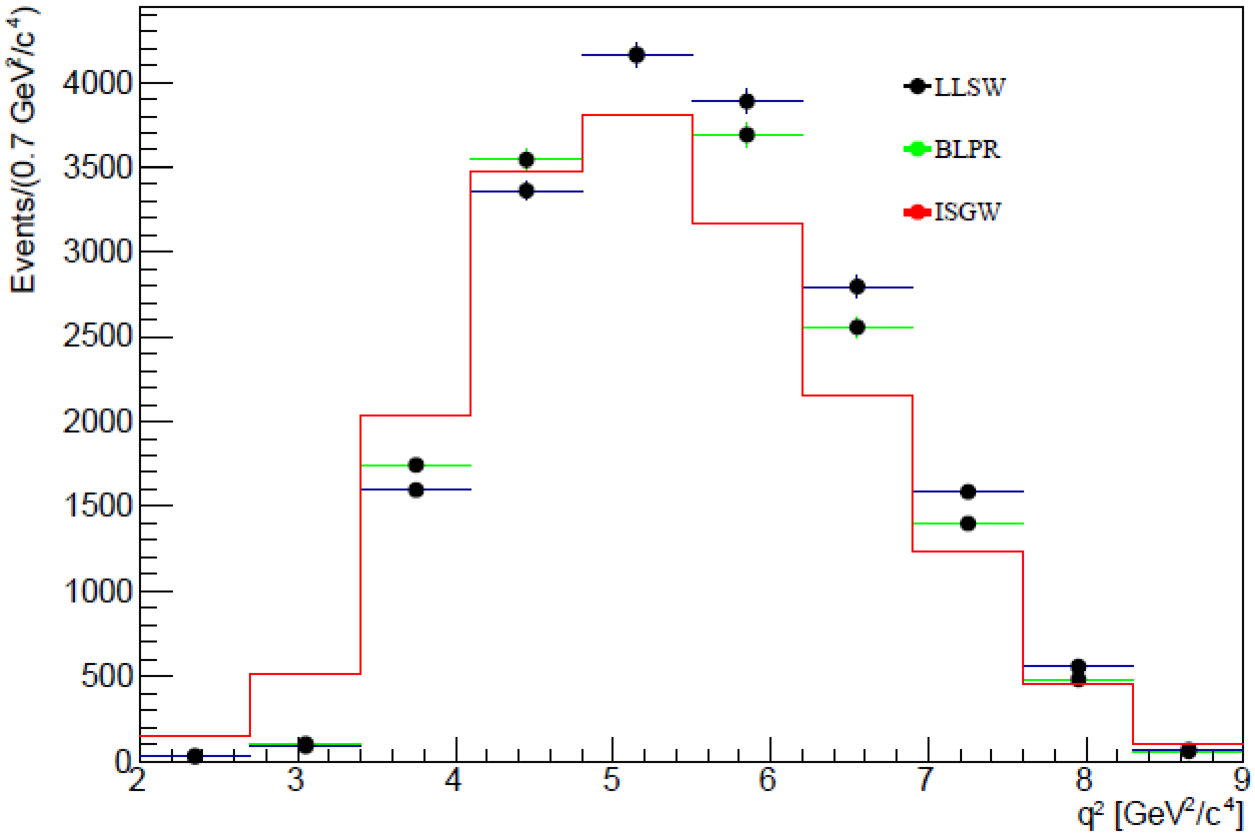
- The fit is repeated forcing the signal to 0
- To include systematic uncertainty in the significance, the $D^{**}D_s^{**}$ is left free to float and the D_2/D_1 ratio is allowed to vary
- Based on the χ^2 increase, LHCb can claim evidence for the decay $B^- \to D^{**\circ}\tau^-\nu_\tau$ with a significance of 3.5 σ

Form factor studies with HAMMER

- Studies performed in contact with Dean Robinson and Michele Petrucci (Many thanks to them!)
- Three models under scrutiny
  - ISGW2 used for the MC generation
  - BLR : F. Bernlochner, Z. Ligeti, D. Robinson, Phys.Rev. D97 (2018) 075011
  - LLSW A. K. Leibovich, Z. Ligeti, I. W. Stewart and M. B. Wise, Phys.Rev.Lett. 78 (1997) 3995, (hep-ph/970321)
- **Global reweighting used as baseline**
- (Binned reweighting in q^2-$p_{3\pi}$ also checked)

q^2 distribution for the 3 models

LHCb-PAPER-2024-037



q^2 distribution similar for BLR and LLSW but rather different from ISGW

4% change in $D^{**}\tau\nu$ yield

Final systematic uncertainty budget

Source	Relative systematic uncertainty in %
Form factors	3.7
$D_2^*(2460)^0$ fraction	4.4
Finite size of the simulated sample	4.1
Variables and binning choices	5
Other potential background	3.6
Efficiency determination	4.3
Selection and analysis	2
Vertex resolution effects	4.0
WS background description	2
Total	11.4

LHCb-PAPER-2024-037

Preliminary

$B^- \to D^{**0}\tau^-\nu_\tau$ physics results

LHCb-PAPER-2024-037

Preliminary

- Using the normalisation channel yield , one finds:

$$\frac{\mathcal{B}(B^- \to (D_1(2420)^0 + D_2^*(2460)^0)\tau^-\overline{\nu}_\tau)}{\mathcal{B}(B^- \to (D_1(2420)^0 + D_2^*(2460)^0)D_s^{(*)-})} = 0.19 \pm 0.05,$$

- from which

$$\mathcal{B}(B^- \to (D_1(2420)^0 + D_2^*(2460)^0)\tau^-\overline{\nu}_\tau) \times \mathcal{B}(D_1(2420)^0, D_2^*(2460)^0 \to D^{*+}\pi^-) = (0.051 \pm 0.013(\mathrm{stat}) \pm 0.006\,(\mathrm{syst}) \pm 0.009(\mathrm{ext}))\%,$$

- and

$$\mathcal{R}(D_1(2420)^0 + D_2^*(2460)^0) = 0.13 \pm 0.03\,(\mathrm{stat}) \pm 0.01\,(\mathrm{syst}) \pm 0.02(\mathrm{ext}).$$

SM prediction is 0.09 ±.02 :This result is compatible with SM within 1 σ

Feed-down into R(D*) analysis

- A $D^{**}\tau\nu$ event can be reconstructed as a signal in D** analysis or can end up as a background event in the R(D*) fit
- The subtraction rate in the LCHb-PAPER-2022-51 hadronic τ R(D*) publication is based on SM theoretical prediction
- Using the simulation, one can measure the probability that an D** candidate ends up either as D** signal or as the R(D*) feeddown.
- One measures as well the D^{**0} vs D^{**+} feed-down probability
- An experimental upper limit of 13.1 % events at 95 % c.l of D** feed-down in R(D*) and a prediction of 8.9%±2.1% has been established.
- It is larger but compatible at 2.9 σ level with present estimate of subtraction level.

LHCb-PAPER-2024-037

Preliminary

Conclusions

- Evidence has been obtained for the decay $B^{-}\rightarrow D^{**\circ}\tau^{-}\nu_{\tau}$ at 3.5 σ level : first ever measurement of this decay

$$\mathcal{B}(B^{-} \to (D_1(2420)^0 + D_2^*(2460)^0)\tau^{-}\overline{\nu}_{\tau}) \times \mathcal{B}(D_1(2420)^0, D_2^*(2460)^0 \to D^{*+}\pi^{-}) = (0.051 \pm 0.013 (\text{stat}) \pm 0.006\,(\text{syst}) \pm 0.009(\text{ext}))\%,$$

- Preference for D_1 dominance at 2σ level.
- R(D**°) has been measured in agreement with SM model prediction of 0.09 ± 0.02

$$\mathcal{R}(D_1(2420)^0 + D_2^*(2460)^0) = 0.13 \pm 0.03\,(\text{stat}) \pm 0.01\,(\text{syst}) \pm 0.02(\text{ext}).$$

- The D** feed-down fraction in LHCb R(D*) paper has been found to be 8.9%±2.1%

LFU Prospects using hadronic τ decays in LHCb

- The basis of the hadronic τ analysis in LHCb formulated 10 years ago!
- Since then :
  - **Measurement of R(D*) in 2017 (Run1) and 2022 (2 fb-1 of Run2 data)**
    (LHCb-PAPER-2017-027 and LHCb-PAPER-2022-052)
  - **Measurement of R(Λ_c) using Run1 data in 2021 (LHCb-PAPER-2021-044)**
  - **Measurement of D* polarization in D*$\tau\nu$ decays in 2023 (LHCb-PAPER-2023-020)**
  - **Measurement of R(D**) today (LHCb-PAPER-2024-037)**

$$q^2 < 7\,\mathrm{GeV}^2/c^4 : \quad 0.51 \pm 0.07\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst}),$$
$$q^2 > 7\,\mathrm{GeV}^2/c^4 : \quad 0.35 \pm 0.08\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst}),$$
$$q^2 \text{ whole region} : \quad 0.43 \pm 0.06\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst}),$$

- In preparation
- **Measurement of R(D*) with the full Run1-Run2 statistics**
- **R(Λ_c) and R(J/ψ) at a later stage**
- **Full angular analysis for D*$\tau\nu$ decays (on a somewhat longer term)**

Backup slides

Relative rates in D*+ final states using R(D**) from theory and measured D**$\mu\nu$

- $BR(B^+ \rightarrow D_1(2420)^\circ\tau\nu; D^\circ_1 \rightarrow D^{*+}) = 3\ 10^{-4}$ (BR all= 0.075%
- $BR(B^+ \rightarrow D_2(2460)^\circ\tau\nu); D^\circ_2 \rightarrow D^{*+}) = 0.7\ 10^{-4}$ (0.028%
- $BR(B^+ \rightarrow D'_1(2430)^\circ\tau\nu); D'^\circ_1 \rightarrow D^{*+}) = 1.35\ 10^{-4}$ 0.02%)

- $BR(B^\circ \rightarrow D1(2420)^+\tau\nu; D_1^+ \rightarrow D^{*+}) = 1.4\ 10^{-4}$ (BR all= 0.067%
- $BR(B^\circ \rightarrow D2(2460)^+\ \tau\nu); D_2^+ \rightarrow D^{*+}) = 0.34\ 10^{-4}$ 0.026%
- $BR(B^\circ \rightarrow D'1(2430)^+\ \tau\nu); D'^+_1 \rightarrow D^{*+}) = 0.75\ 10^{-4}$ 0.025%

Note: in DECAY.DECAY the total BR are .13%,.2% and .2% respectively!!!
The BR to D^{*+} are 2/3 for $D^{**\circ}$ and 1/3 for D^{**+}

Fits results

Method	Signal Yield	c2
ISGW	120.3±22.8	110.2
BLPR-2D	122.9±23.8	112.0
LLSW-2D	111.2±21.1	110.5
BLPR-Full reweighting	120.7±21.4	102.6
LLSW-Full reweighting	124.7±20.9	103.6

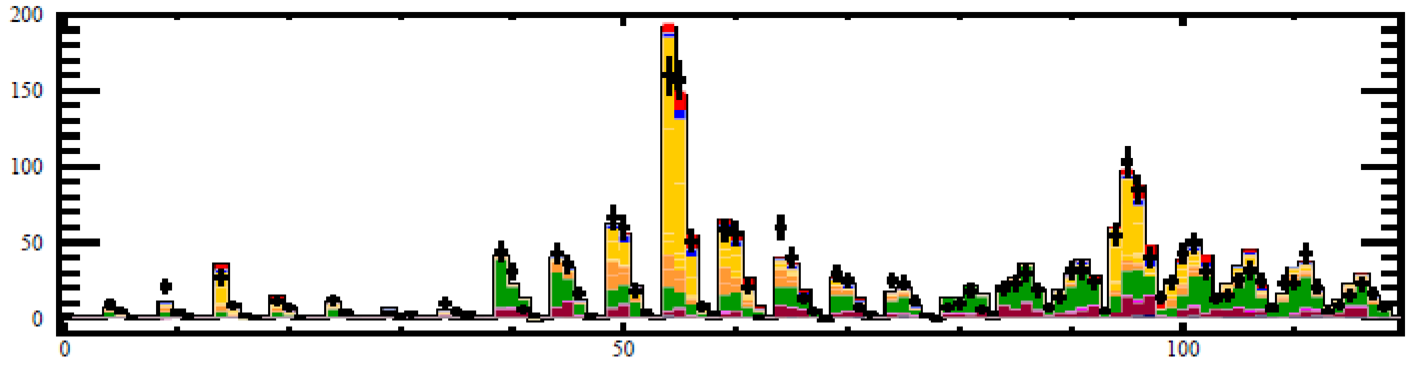
Based on these results, we assign a 4% systematic uncertainty , half of the largest difference observed.

Systematic wrt binning and fit variables

Fit variables	Binning	$(D_1^0(2420)D_2^{*0}(2460))\tau\nu_\tau$	$D_1^{'0}(2400)\tau\nu_\tau$
BDT-Δm-q^2 (nominal)	5x8x3	120.3$\pm$22.8	100.0
BDT-Δm	5x10	97.7$\pm$27.5	57.5
BDT-Δm-q^2	5x10x4	120.4$\pm$21.5	107.7
BDT-Δm-q^2	5x8x2	111.7$\pm$25.2	78
BDT-Δm_q^2-cosθ	5x21x5	132.5$\pm$18.1	159
BDT-Δm-q^2_{D**}	5x8x4	115$\pm$25.7	74.3
BDT-Δm-cosθ	5x8x6	118$\pm$22.7	96.6

Flattened distributions for the 120 bins

LHCb Preliminary
9 fb^{-1}



Effect on R(D*) on the hadronic R(D*) results (LHCb-PAPER-2022-051)

- D** $\tau\nu$ subtracted rate is 3.5 % : 2.1% from B° and B^+, 1.4% from B_s
- This new result indicates a higher subtraction rate from B° and B^+

of 8.9%±2.1%

  - Higher R
  - Higher D'_1 rate
- Leaving the B_s contribution constant, this would shift down 2015-2016 R(D*) result by 6.8 %, ie ~6% for the combined Run1-2015-2016 result
- This would represent 1 σ of systematic uncertainty and 0.7 σ for the total uncertainty for this measurement

D**τν feed down simulated prediction in the published result

Index j	State	$D^{**}\tau\nu$ yield	Weight	Weighted yield N_j
1	$D_1(2420)^0$	124	0.3497	43.36
2	$D_2(2460)^0$	54	0.1667	9.00
3	$D_1'(2430)^0$	186	0.1023	19.03
4	$D_1(2420)^+$	175	0.3263	57.10
5	$D_2(2460)^+$	95	0.1225	11.64
6	$D_1'(2430)^+$	267	0.1174	31.35
7	from D_{s1}'	222	0.5	111
	Total	1123		282.48

LHCb simulation 8.1k D*τν signal

$D^{**}\tau\nu$ feed down new simulated prediction

Particle	Yield	Weighted yield
D_1(2420)0	1171.5	409.7
D*_2(2460)0	531.2	88.6
D_1(H)0	1748.1	178.8
D_1(2420)+	1663.1	542.7
D*_2(2460)+	812.5	99.5
D_1(H)+	2528.1	296.8
D_s1(2536)+	1780.7	302.7
D*_s2+	163.6	81.8

LHCb simulation 81k $D^{*}\tau\nu$ signal