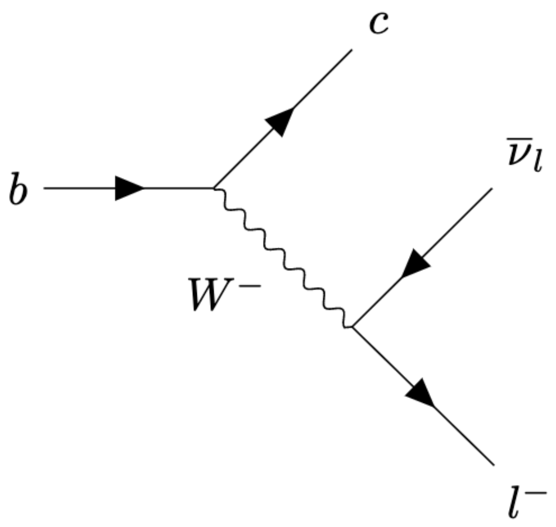
Lepton Flavour Universality tests at LHCb

Rizwaan Mohammed, on behalf of the LHCb Collaboration
University of Oxford

Outline

- Lepton Flavour Universality (LFU) is an accidental symmetry of the Standard Model
- Predicts that each lepton generation has identical coupling to gauge bosons, differences in decay rates are only due to masses
- Today, will cover LFU tests in τ and μ modes, with tree-level $b \to cl\nu$ decays
- LHCb also tests LFU in μ and e modes, with loop-level $b \to sll$ decays, see talk by Florian for more details



$R(D^*)$ measurements at LHCb

$$R\left(D^{(*)}\right) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\mu\nu_\mu)}$$

Muonic	Hadronic
• $\tau \to \mu\nu\bar{\nu}$	• $\tau \to \pi\pi\pi(\pi^0)\bar{\nu}$
• Measure τ and μ modes in one dataset	• Need external BR measurements for normalisation
• Large statistics	• Precise reconstruction of τ vertex
• Can measure $R(D^0)$ and $R(D^*)$ simultaneously	• No muonic background

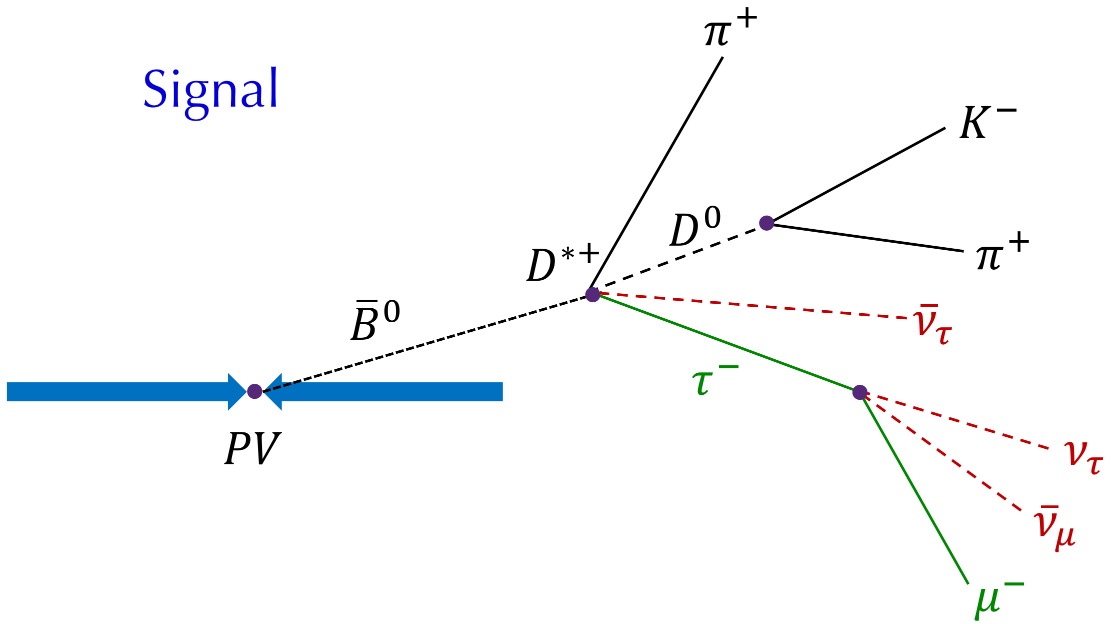
Combined measurement of R(D^0) and R(D^*)

LHCB-PAPER-2022-039

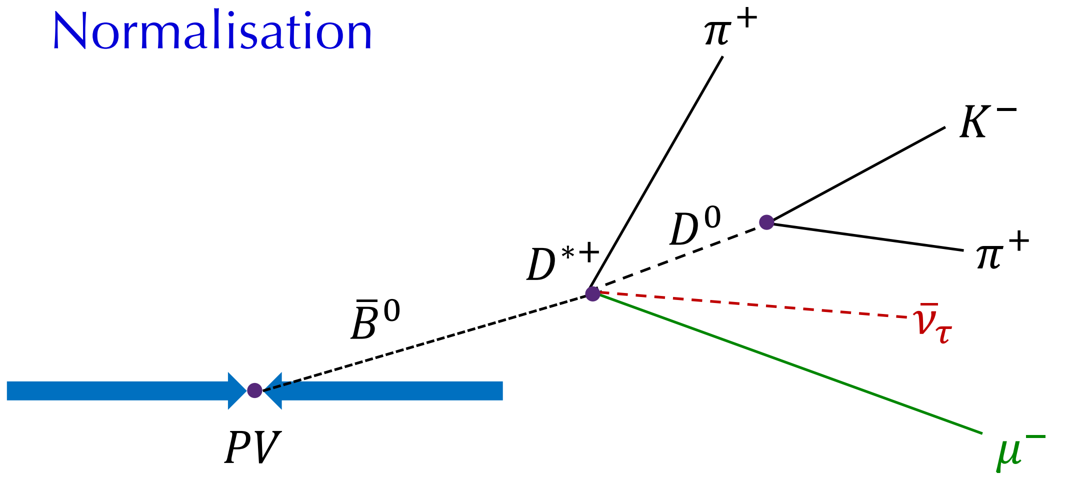
R(D^0) - R(D^*) muonic

LHCB-PAPER-2022-039

- Uses Run 1 LHCb data (3 fb^{-1})
- Muonic τ decay has large branching fraction (17.4%)
- Make measurement of R(D^0) and R(D^*) using the same dataset
- Split dataset into two samples:
  - $\{D^0\mu\}$ - Veto $D^{*+} \to D^0\pi^+$
  - $\{D^*\mu\}$ - Combine D^0 with slow pion
- $\{D^0\mu\}$ ~5 times larger due to higher branching fraction and efficiency
- Muonic decay used as normalisation, ~20 times larger than signal



Signal



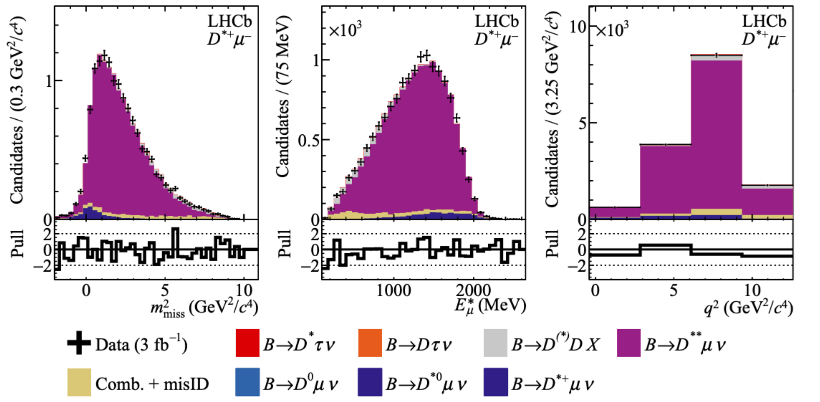
Normalisation

Control regions

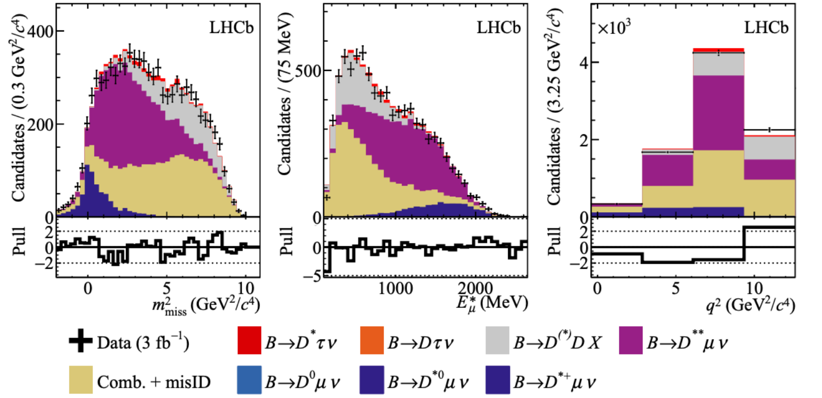
LHCB-PAPER-2022-039

Use 3 separate control regions:

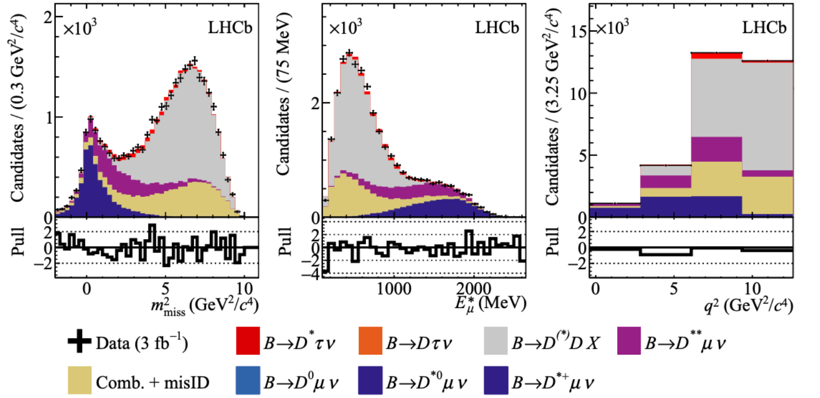
$B \rightarrow (D^{**} \rightarrow D^{*}\pi)l\nu$ - “One pion sample”



$B \rightarrow (D^{**} \rightarrow D^{*}\pi\pi)l\nu$ - “Two pion sample”

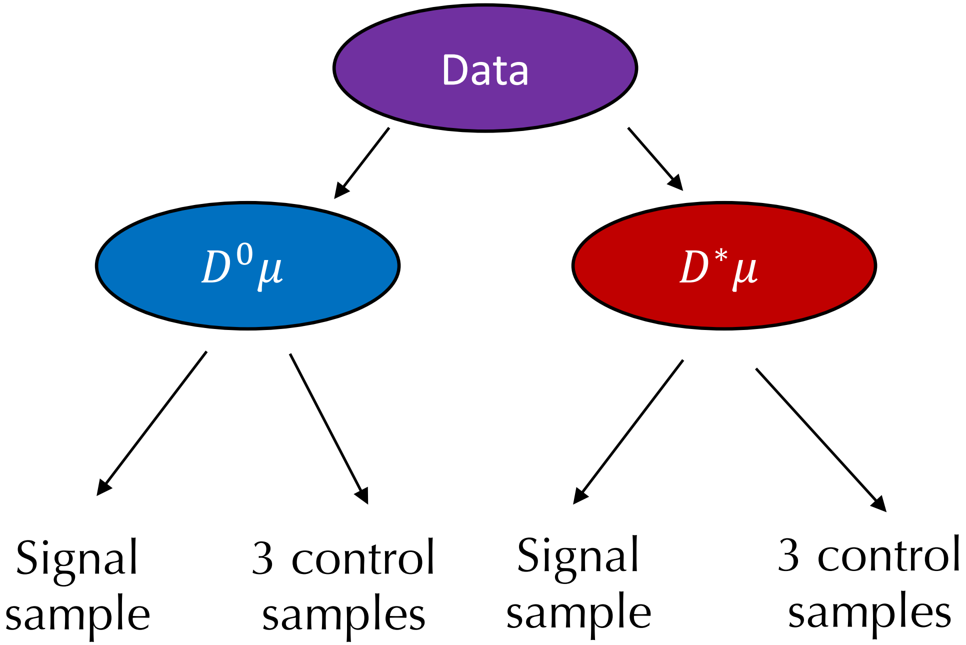


$B \rightarrow D^{(*)}DX$– “Kaon sample”



Fit strategy

- 3D template fit in q^2, m_{miss}^2, E_l^*, approximate B meson rest frame
- Fit 8 samples simultaneously
- Use two fully independent fitters, independent implementations
- Confirm agreement between two fitters
- Form factor (FF) models:
  - D^* : BGL [JHEP 12 (2017) 060]
  - D^0 : BCL [PRD 92 (2015) 054510]
  - D^{**} : Bernlochner & Ligeti [PRD 95 (2017) 014022]
- Helicity-suppressed terms constrained and other FF params are inferred from fit.



$$m_{miss}^2 = \left(p_B - p_{D^{(*)}} - p_l\right)^2$$

$$q^2 = \left(p_B - p_{D^{(*)}}\right)^2$$

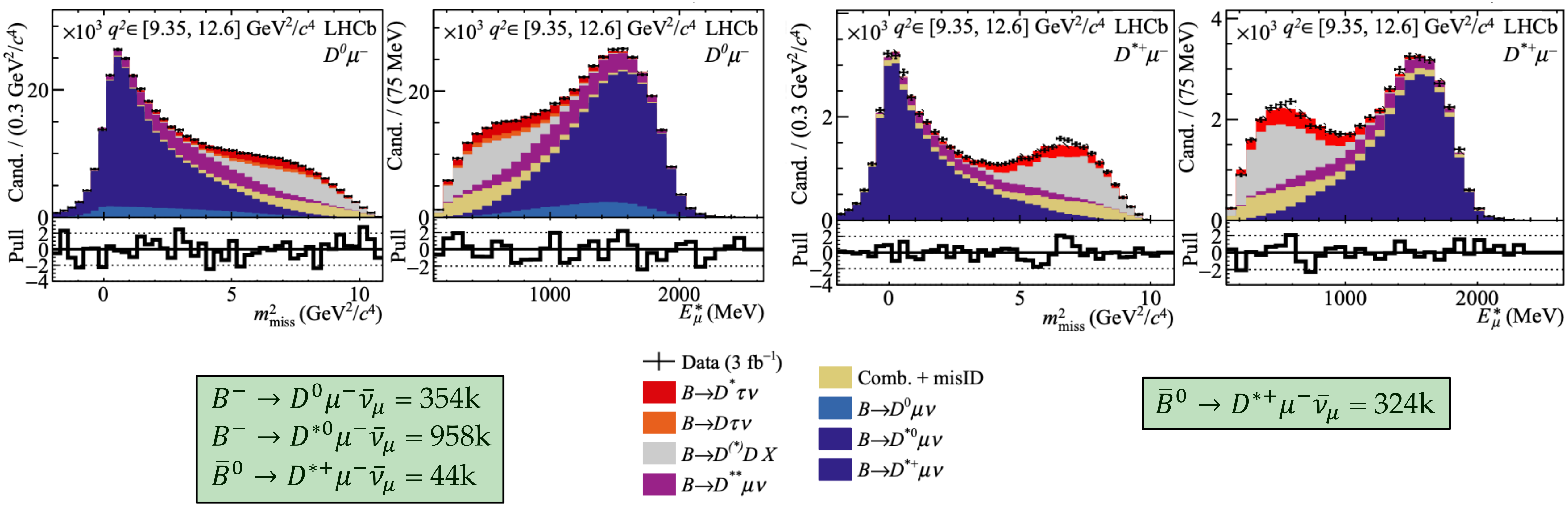
Fit projections

LHCB-PAPER-2022-039

- 4 bins are used in q^2, projections in highest bin are shown

$D^0\mu$ sample

$D^*\mu$ sample



$B^- \to D^0\mu^-\bar{\nu}_\mu = 354$k
$B^- \to D^{*0}\mu^-\bar{\nu}_\mu = 958$k
$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu = 44$k

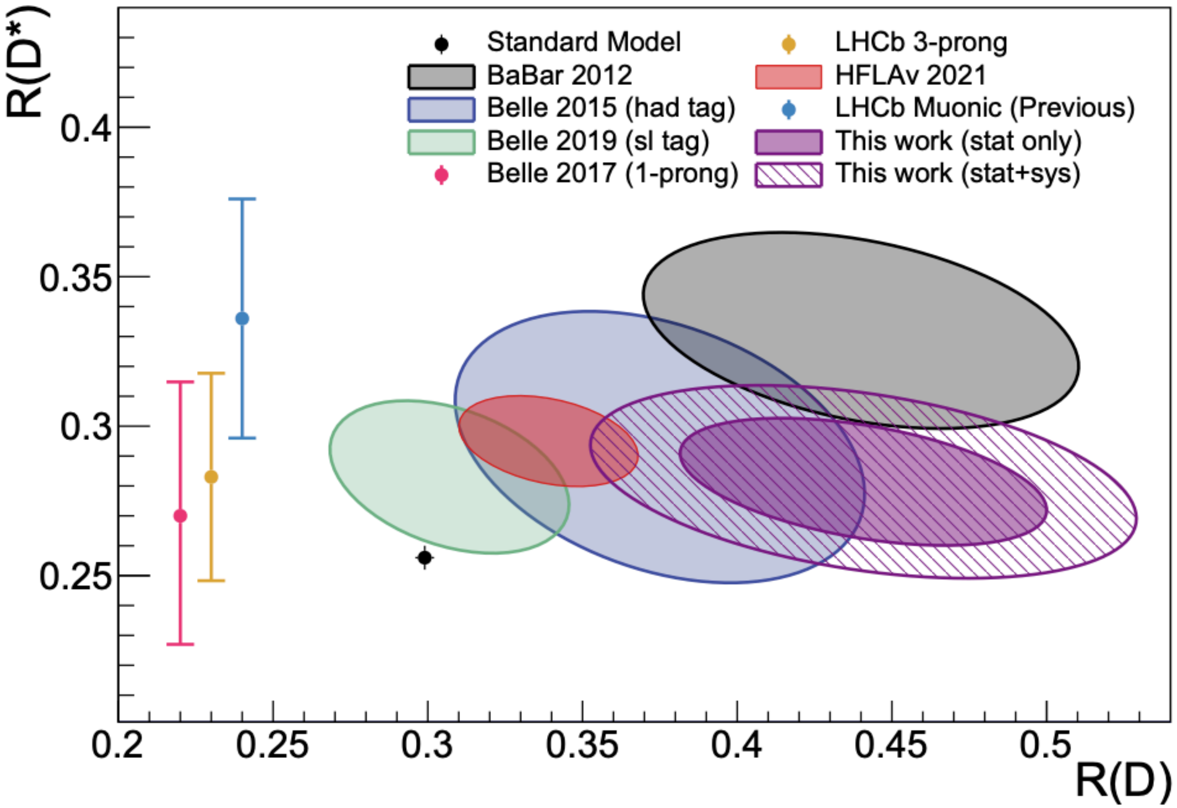
$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu = 324$k

Result

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

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

- $\rho = -0.43$
- 1.9σ agreement with SM
- Main systematic uncertainties are from sizes of templates and background shapes ($B \rightarrow D^* D X$ and $B \rightarrow D^{**} \mu \nu$)



Taken from CERN Seminar

Measurement of R(D^*) with hadronic τ decays

LHCB-PAPER-2022-052

R(D^*) hadronic

LHCB-PAPER-2022-052

- Update of Run 1 measurement, using data from 2015 and 2016 (2 fb^{-1})
- Use a normalisation mode, then extract R(D^*) using external branching fraction as input
- Knowledge of external branching fraction contributes a systematic uncertainty
- However, if we normalised to muonic mode directly, there would be larger systematic uncertainty from efficiency
- Therefore measure signal fraction relative to $B^0 \to D^{*-}\pi^+\pi^-\pi^+$

Measure:

$$\kappa(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}$$

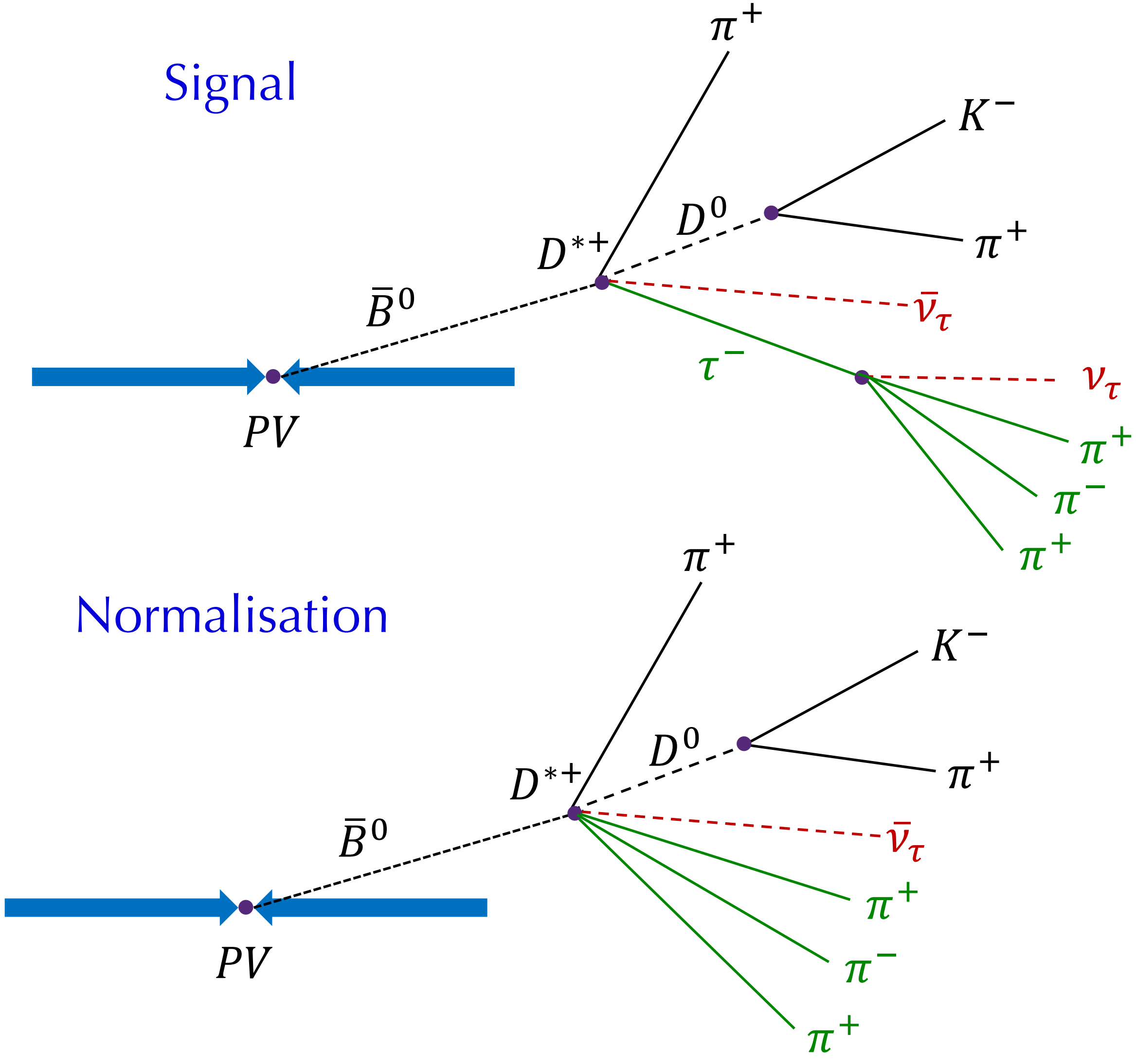
From simulation

$$\kappa(D^*) = \frac{N_{sig}}{N_{norm}}\frac{\epsilon_{norm}}{\epsilon_{sig}}\left\{\frac{1}{\mathcal{B}(\tau^+ \to 3\pi\bar{\nu}_\tau) + \mathcal{B}(\tau^+ \to 3\pi\pi^0\bar{\nu}_\tau)}\right\}$$

$$R(D^*) = \kappa(D^*)\underbrace{\left\{\frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}\right\}}_{\text{External branching fraction input [PDG]}}$$

R(D^*) hadronic

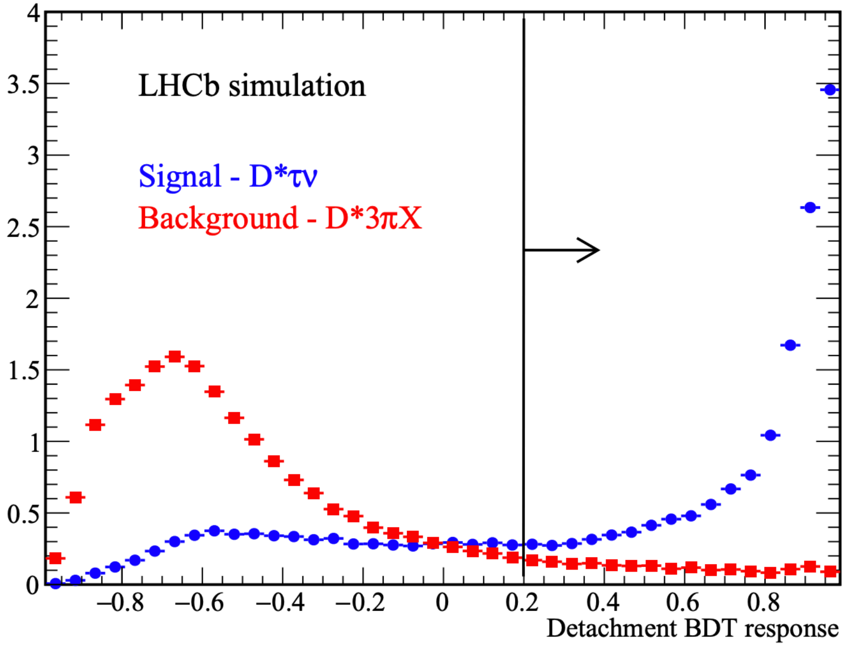
- ~40% more candidates than previous work (higher energy, better trigger)
- No muonic background, but large background from $\bar{B}^0 \to D^{*+}3\pi X$
- Also large double charm background ($B \to D^* D X$)
- $\tau \to 3\pi(\pi^0)$ decay has branching fraction of 13.5%
- Approximate rest frames of B and τ due to missing neutrinos



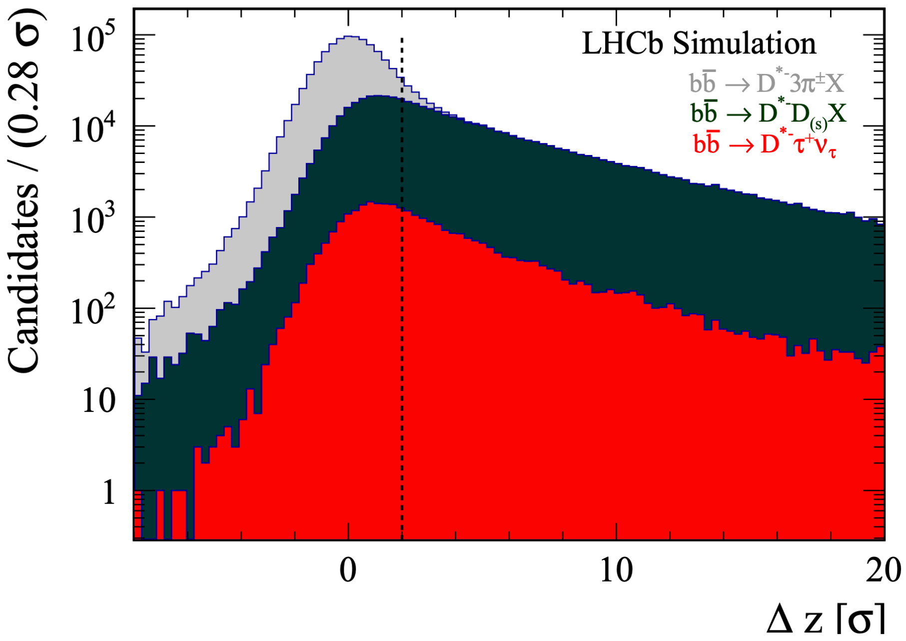
$B \to D^{*}3\pi X$ background

LHCB-PAPER-2022-052

- Very large background
- Can reduce by using 3π vertex information – must be displaced from B vertex in signal mode
- Use vertex separation variables in a BDT classifier, gives > 99% background rejection



$$\Delta(z) = z(3\pi) - z(B^0)$$

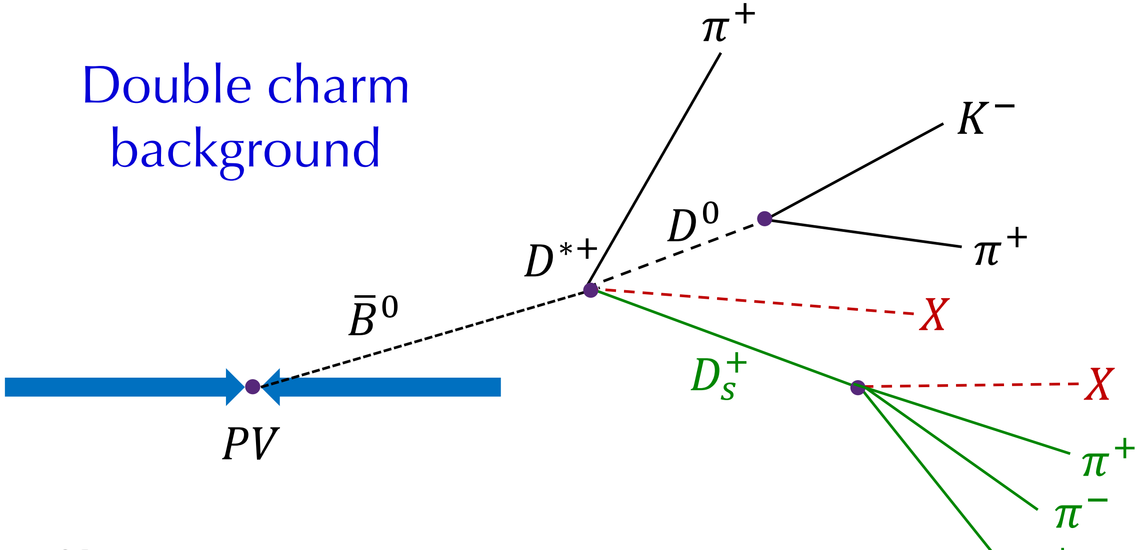


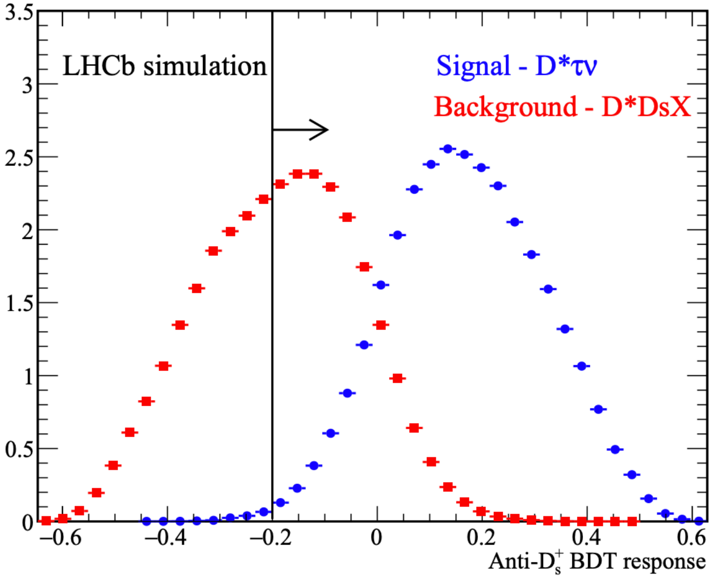
Double charm background

LHCB-PAPER-2022-052

- Another large background comes from $B^{(0)}_{(s)} \rightarrow D^{*-} D_s^{+} (\rightarrow 3\pi X) X$ events
- Most abundant background after full selection
- These can mimic the signal topology
- Train "anti-D_s^+" BDT to reject these decays
- Use isolation and kinematic variables in training
- The BDT is also used as a fit variable

Double charm background



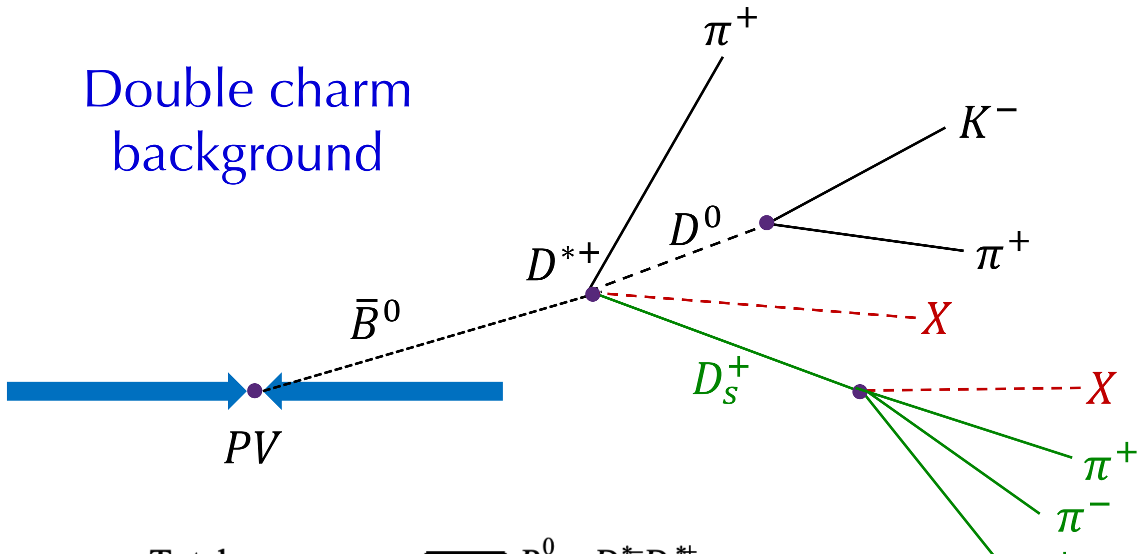


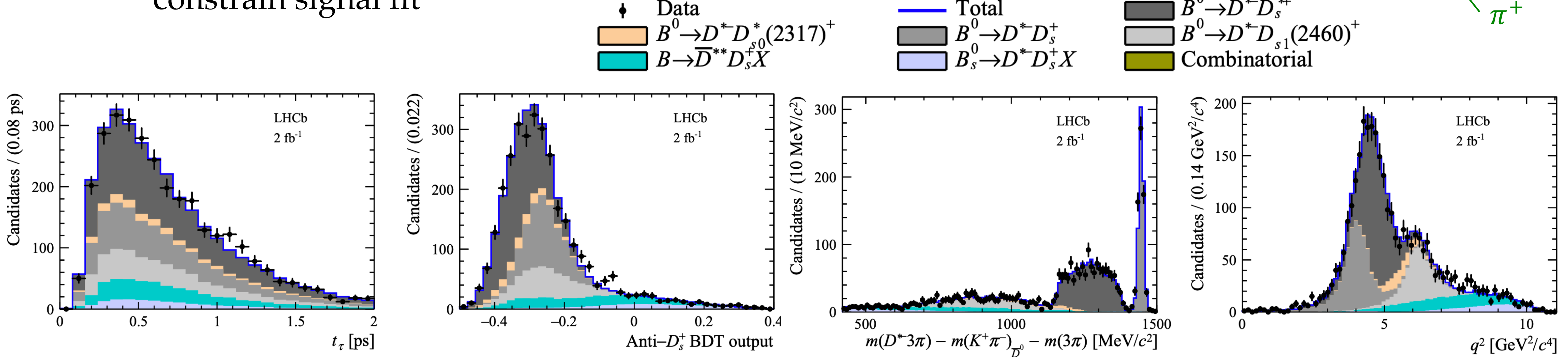
Double charm background

LHCB-PAPER-2022-052

- Another large background comes from $B_{(s)}^{(0)} \rightarrow D^{*-} D_s^+ (\rightarrow 3\pi X) X$ events
- Most abundant background after full selection
- Measure production fractions of these decays in separate fit, then use this to constrain signal fit

Double charm background



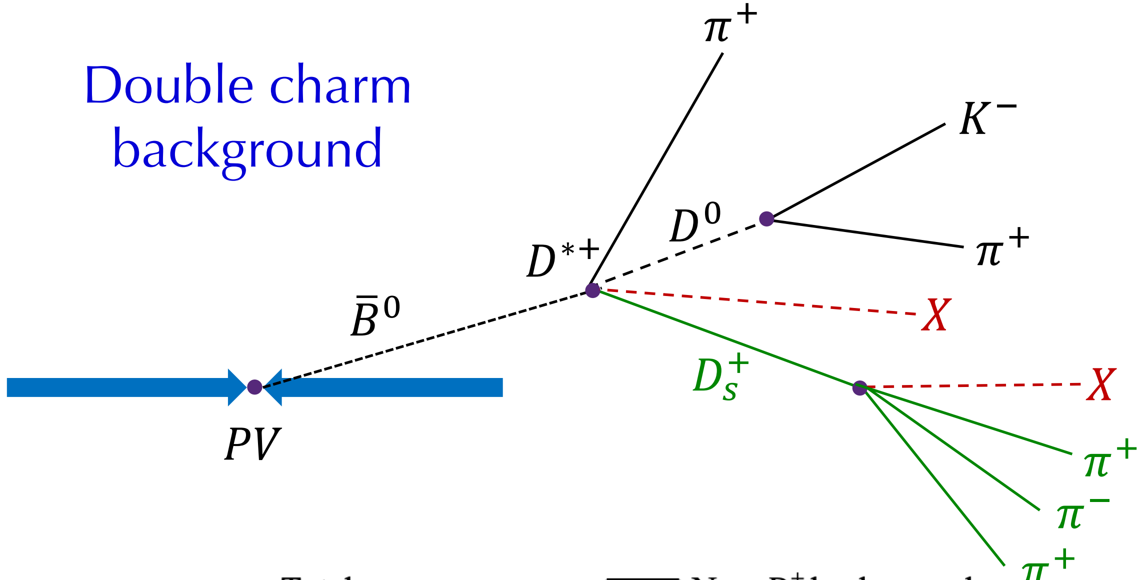


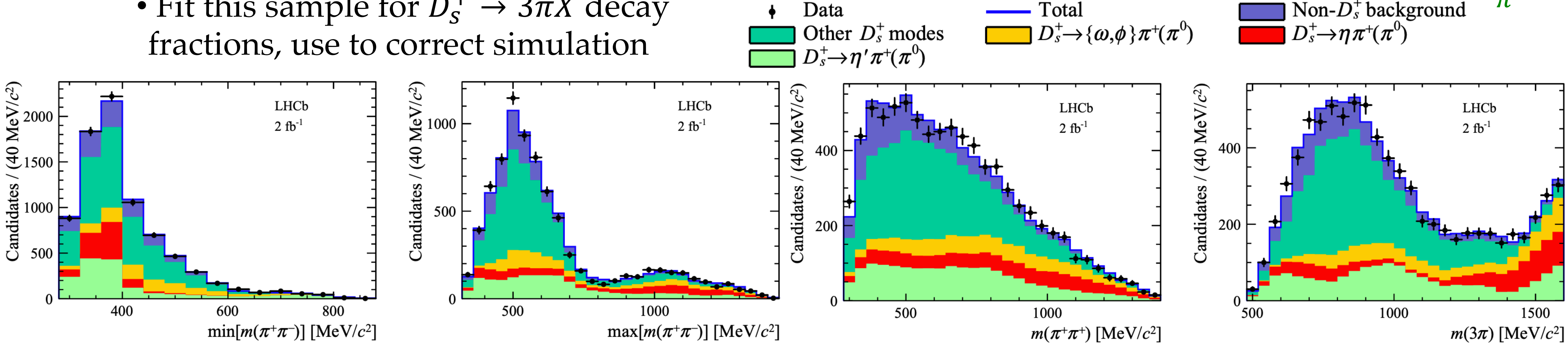
Double charm background

LHCB-PAPER-2022-052

- Another large background comes from $B_{(s)}^{(0)} \rightarrow D^{*-} D_s^+ (\rightarrow 3\pi X) X$ events
- Most abundant background after full selection
- Can invert the cut on the anti-D_s^+ BDT to obtain control sample in data
- Fit this sample for $D_s^+ \rightarrow 3\pi X$ decay fractions, use to correct simulation

Double charm background





Fit strategy

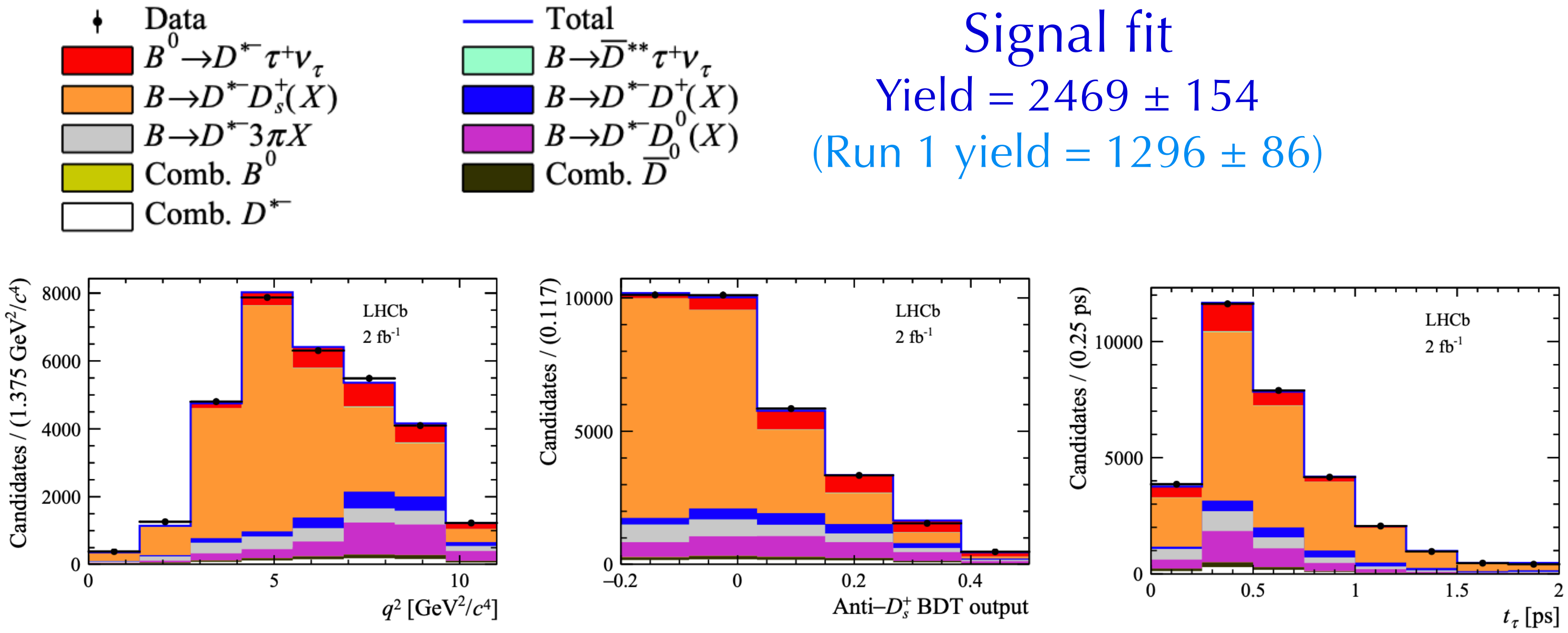
LHCB-PAPER-2022-052

- 3D maximum likelihood template fit, using: $\{q^2$, anti-D_s^+ BDT, τ lifetime$\}$
- 8 bins in q^2 and τ lifetime, 6 bins in BDT output
- This fit is used to extract $B^0 \to D^{*-}\tau^+\nu_\tau$ yield
- $B^0 \to D^{*-}3\pi$ yield obtained from separate normalisation fit

Signal fit

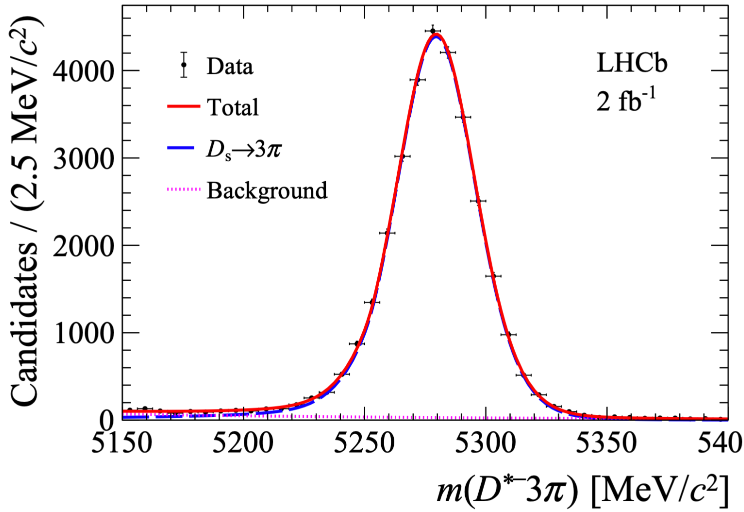
Yield = 2469 ± 154

(Run 1 yield = 1296 ± 86)



Normalisation fit

Yield ~ 30k



Result

LHCB-PAPER-2022-052

$$\kappa(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)} = 1.700 \pm 0.101\,(stat)\,^{+0.105}_{-0.100}\,(syst)$$

Main systematic uncertainties are template sizes and background template shapes

This gives absolute branching fraction:

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

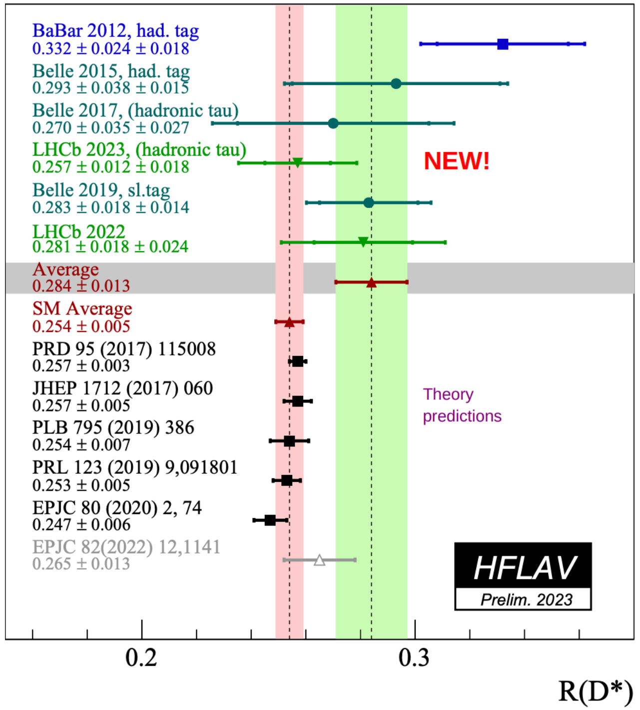
From this analysis:

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

Combining with previous (Run 1) result:

$$\boxed{R(D^*) = 0.257 \pm 0.012\,(stat) \pm 0.014\,(syst) \pm 0.012\,(ext)}$$

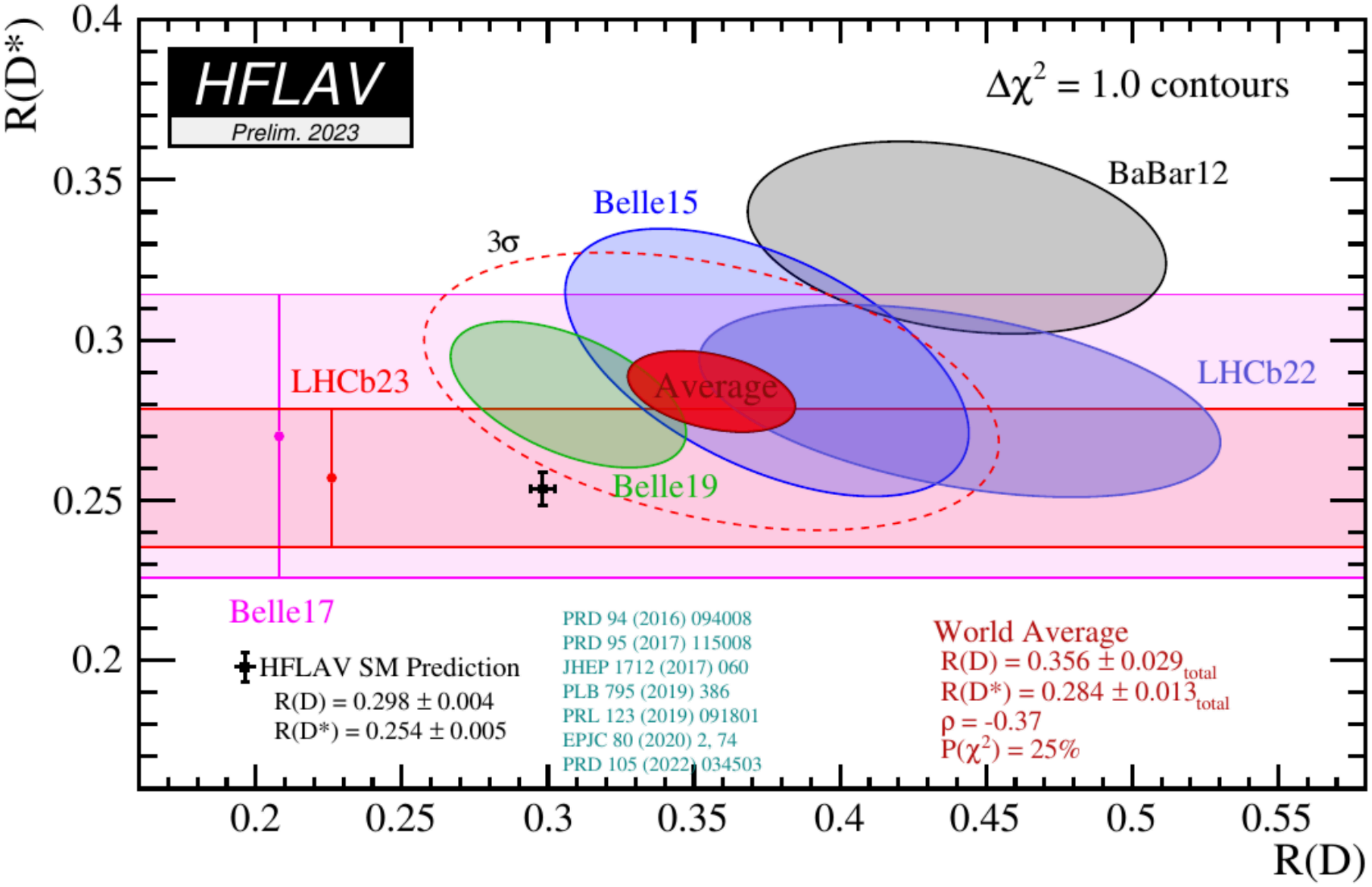
From HFLAV



Consistent with SM within 1σ

Updated world average

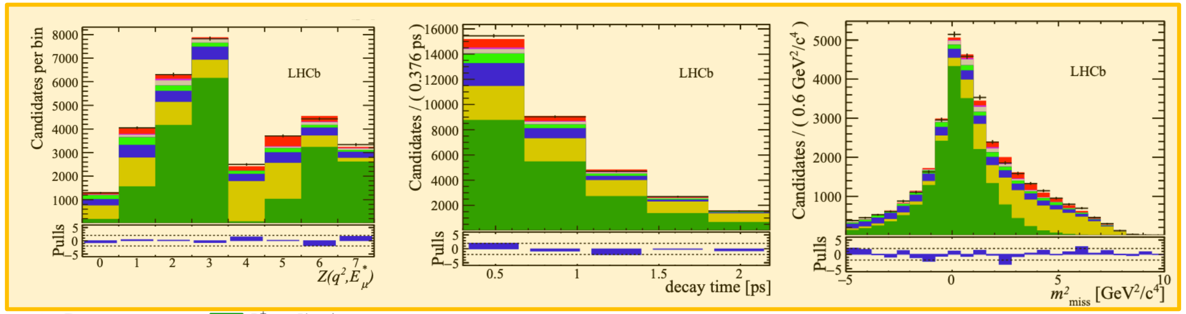
- With two new results (LHCb22, LHCb23), world average becomes:
    - $\boldsymbol{R(D^*) = \ 0.284 \pm 0.013}$
    - $\boldsymbol{R(D) = 0.356 \pm 0.029}$
    - $\boldsymbol{\rho = \text{-}0.37}$
- Deviation from SM for combined $R(D) - R(D^*)$ moves from **3.3$\boldsymbol{\sigma}$** to **3.2$\boldsymbol{\sigma}$** with the two new results



From HFLAV

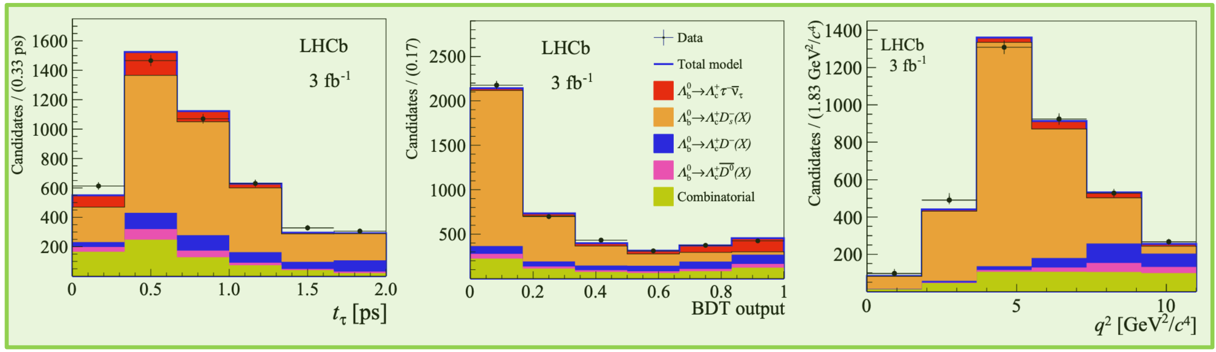
Other measurements

Many other $R(H_c)$ being studied…



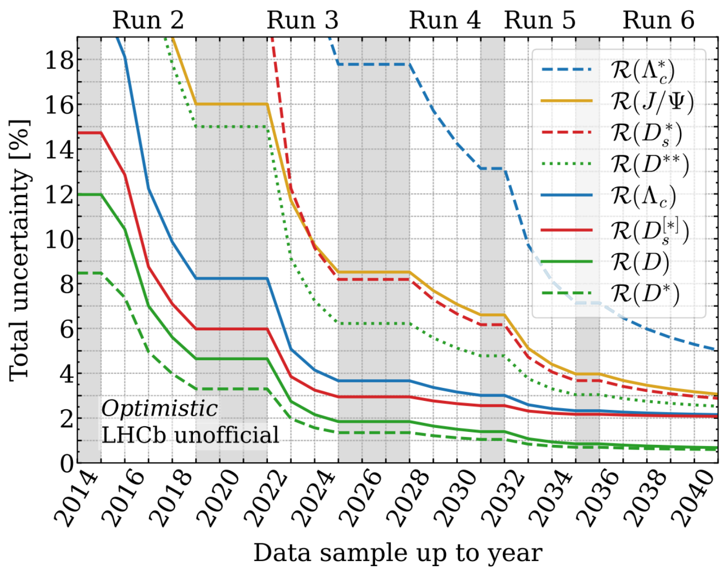
$R(J/\psi)$

[Phys. Rev. Lett. 120 (2018) 121801]



$R(\Lambda_c)$ [Phys. Rev. Lett. 128 (2022) 191803]

	Run 1: 3 fb^{-1} at 7/8 TeV		Run 2: 6 fb^{-1} at 13 TeV	
mode	muonic	hadronic	muonic	hadronic
$R(D^+)$	✗	✗	✗	✗
$R(D^0)$	✔	✗	✗	✗
$R(D^*)$	✔	✔	✗	✗
$R(\Lambda_c)$	✗	✔	✗	✗
$R(\Lambda_c^*)$	✗	✗	✗	✗
$R(J/\psi)$	✔	✗	✗	✗
$R(D_s^+)$	✗	✗	✗	✗
$R(D_s^{*+})$	✗	✗	✗	✗



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

Angular analyses

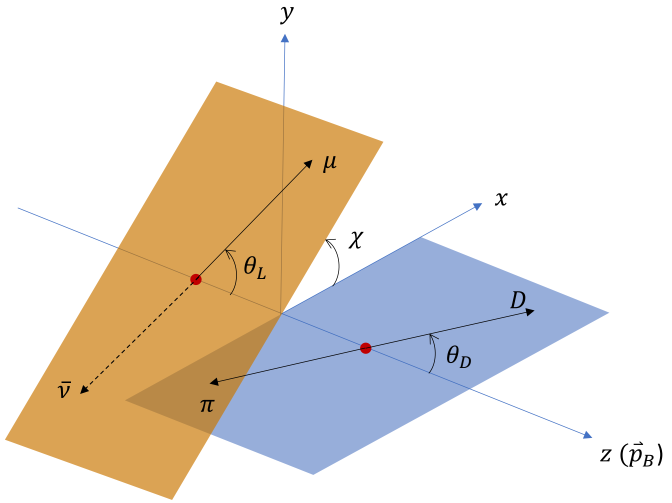
- Measurements of angular decay rate give more complete information than branching ratios – complementary test of LFU

- Different strategies currently being pursued at LHCb:

1. Fit directly for Wilson Coefficients, assuming a particular FF parameterisation

2. Measure angular coefficients with a model independent method

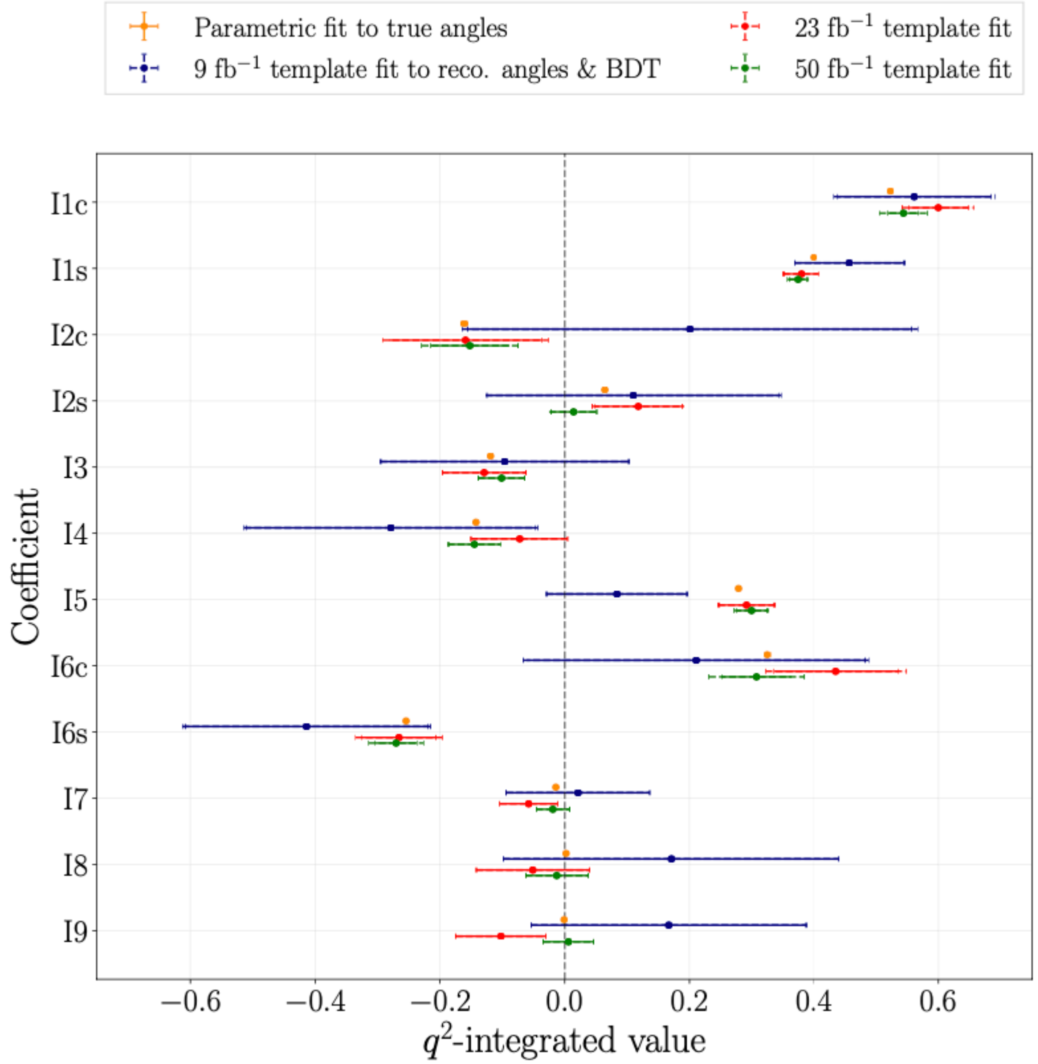
$$\frac{d\Gamma(B \to D^* l\nu)}{dw\ d\cos\theta_l\ d\cos\theta_D\ d\chi} = \frac{3m_B^3 {m_D^*}^2 G_F^2}{16(4\pi)^4}\eta_{EW}|V_{cb}|^2 \sum_i^6 \mathcal{H}_i(w)k_i(\theta_l,\theta_D,\chi)$$



Measuring angular coefficients

- Aim to measure 12 q^2-integrated angular coefficients in $B \to D^* l\nu$ in a model independent way
- Method outlined in proof of concept paper (JHEP 11 (2019) 133)
- Create a template for each angular term, assigning per-event weights to cancel decay model in MC

$$\frac{d^4\Gamma}{dq^2 d(\cos\theta_D) d(\cos\theta_L) d\chi} \propto I_{1c}\cos^2\theta_D + I_{1s}\sin^2\theta_D$$
$$+[I_{2c}\cos^2\theta_D + I_{2s}\sin^2\theta_D]\cos 2\theta_L$$
$$+[I_{6c}\cos^2\theta_D + I_{6s}\sin^2\theta_D]\cos\theta_L$$
$$+[I_3\cos 2\chi + I_9\sin 2\chi]\sin^2\theta_L\sin^2\theta_D$$
$$+[I_4\cos\chi + I_8\sin\chi]\sin 2\theta_L\sin 2\theta_D$$
$$+[I_5\cos\chi + I_7\sin\chi]\sin\theta_L\sin 2\theta_D$$



Conclusions

- LFU tests in $b \rightarrow cl\nu$ are an important component of LHCb's physics program
- Recently released two major measurements of $R(D^0)/R(D^*)$
- Complementary tests with other $R(H_c)$ measurements are being performed
- In addition, angular analyses of $B \rightarrow D^* l\nu$ are ongoing
- Still lots more data to analyse from Run 1 and 2, and have now started Run 3!

Backup

LHCb detector

- Designed to operate in forward region ($2 < \eta < 5$), exploiting large $\sigma_{b\bar{b}}$
- Run 1:

$$\int_{2011}^{2012} \mathcal{L}\ dt = 3\ \mathrm{fb}^{-1}, \sqrt{s} = 7 - 8\ \mathrm{TeV}$$

- Run 2:

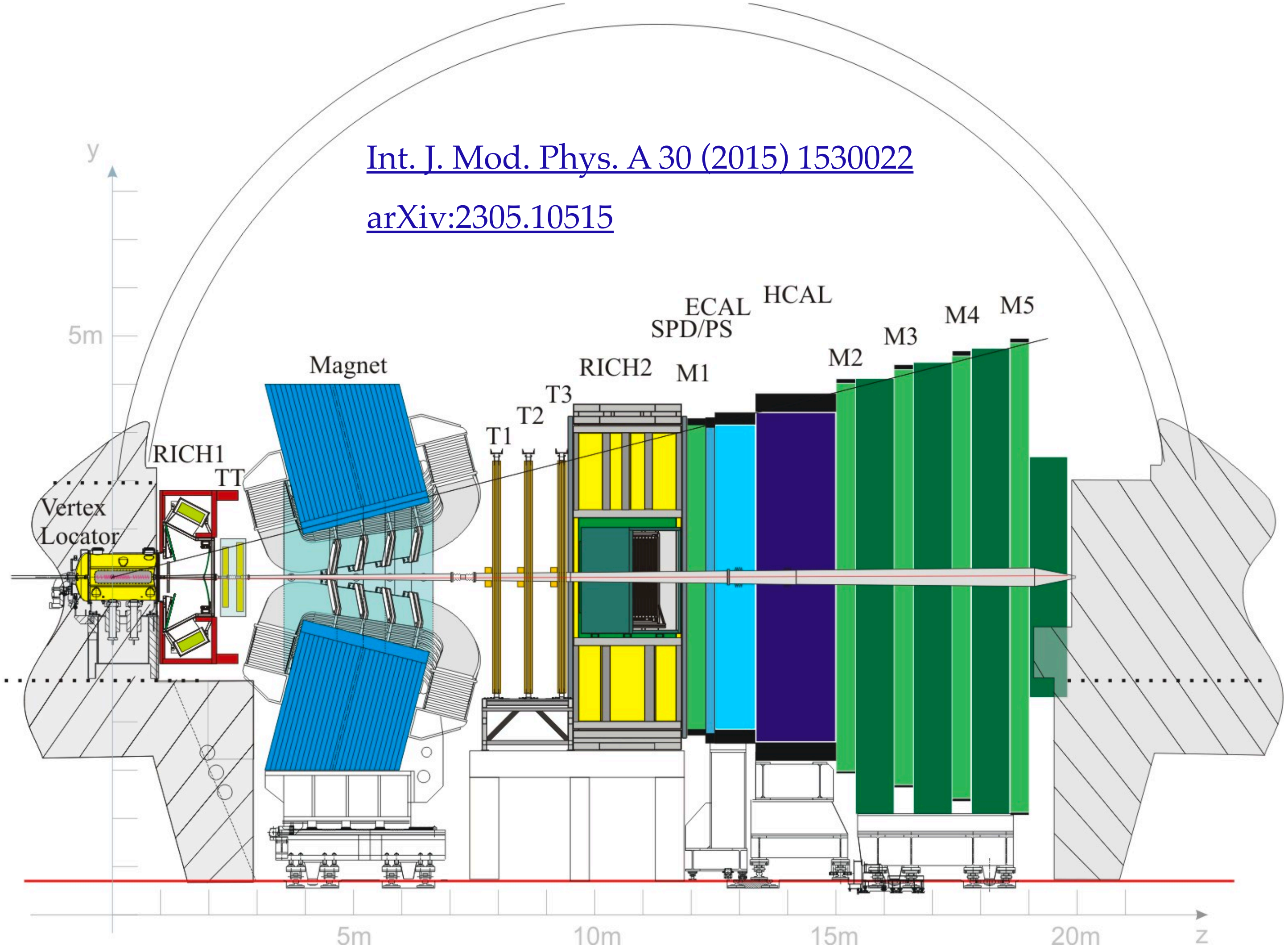
$$\int_{2015}^{2018} \mathcal{L}\ dt = 6\ \mathrm{fb}^{-1}, \sqrt{s} = 13\ \mathrm{TeV}$$

- Run 3: New detector (2023 -),

$\sqrt{s} = 13.6\ \mathrm{TeV}$

Int. J. Mod. Phys. A 30 (2015) 1530022

arXiv:2305.10515



$R(D^*)$ measurements at LHCb

Previous measurements

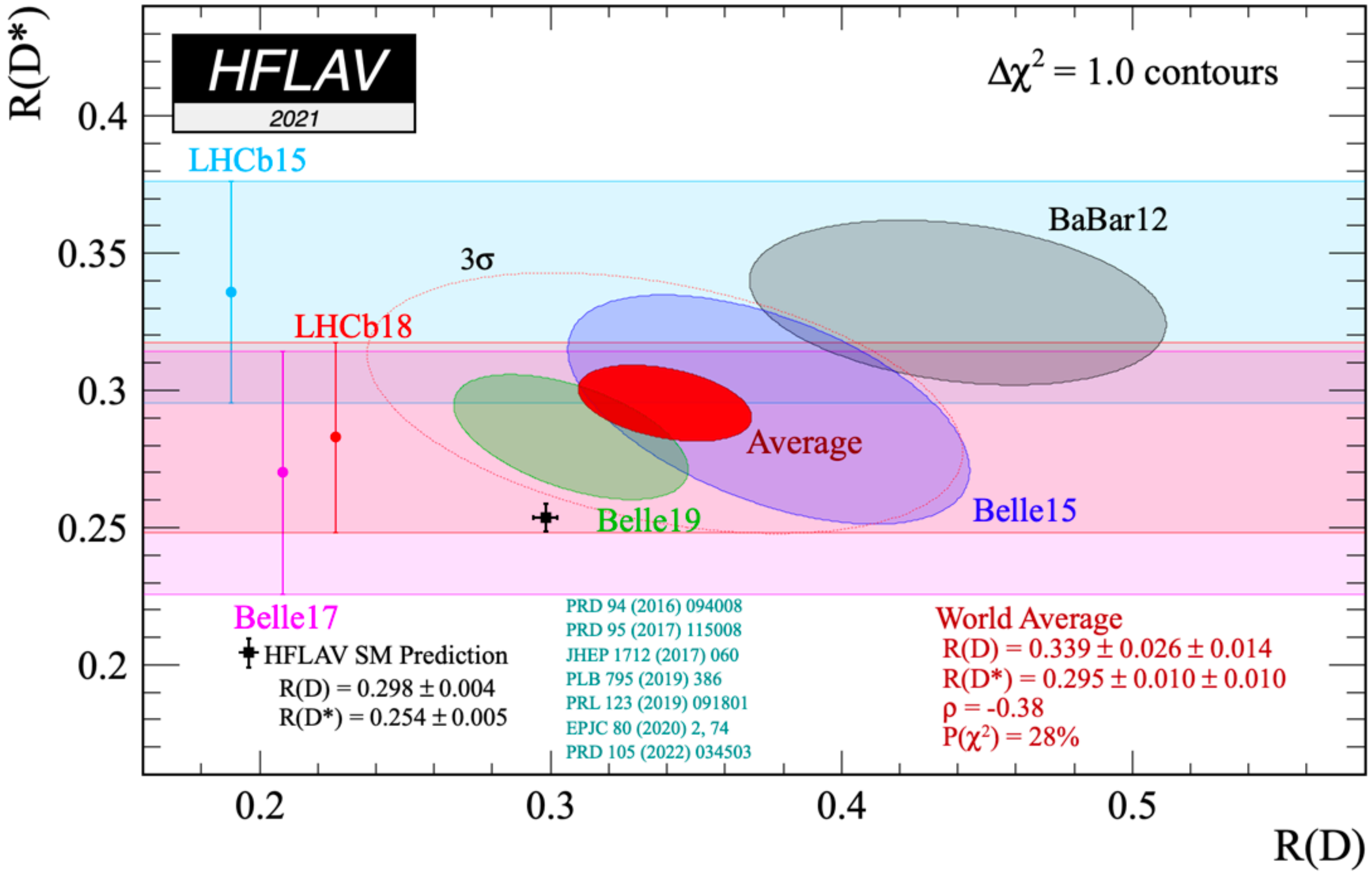
- $R(D^*)$ muonic, Run 1 data [Phys. Rev. Lett. 115, 111803 (2015)]
- $R(D^*)$ hadronic, Run 1 data [Phys. Rev. Lett. 120, 171802 (2018)]

In this talk

- $R(D^0) - R(D^*)$ muonic, Run 1 data [LHCB-PAPER-2022-039, submitted to PRL]
- $R(D^*)$ hadronic, 2015+2016 data [LHCB-PAPER-2022-052, submitted to PRD]

World average status

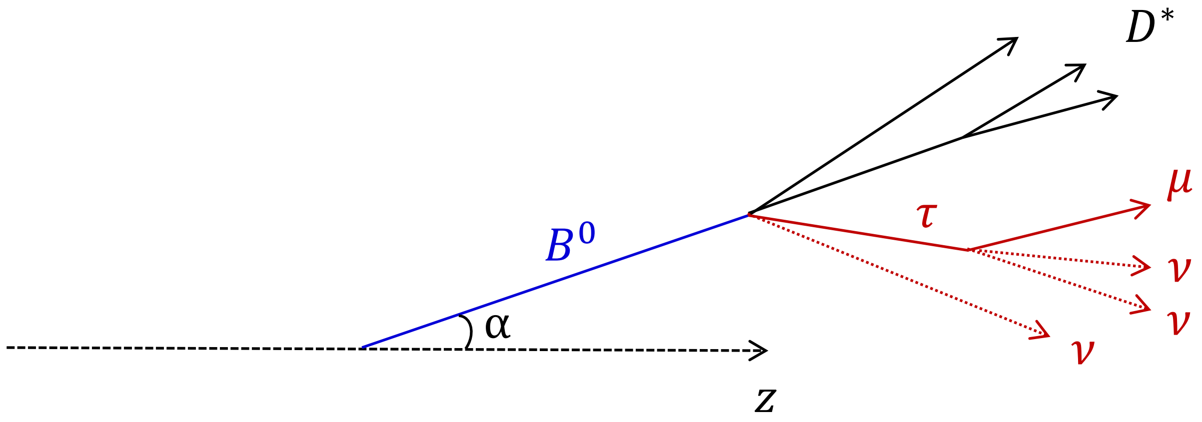
- Status before two new LHCb results
- Contours defined by $\Delta\chi^2 = 1$
- This means horizontal bands represent 68% confidence interval, ellipses are 39%
- Precision of world average is much higher than any measurement
- Longstanding 3.3σ deviation with SM, difficult for this to move with a single measurement



Available at HFLAV

Kinematic reconstruction

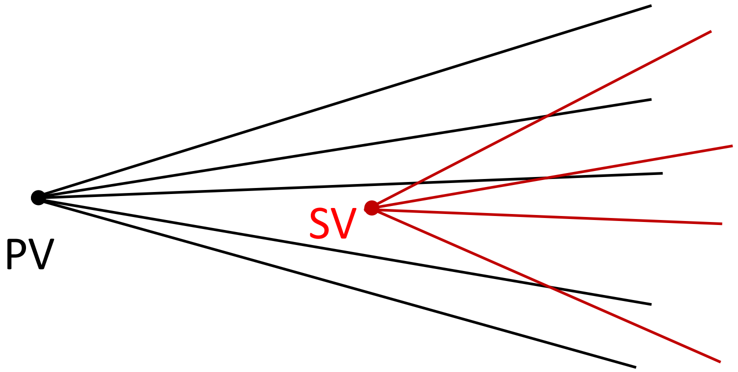
- Missing neutrinos create an experimental challenge, can't fit a clean mass peak
- Can't reconstruct $B\bar{B}$ rest frame at a hadron collider, so need to estimate B momentum
- Assume proper velocity ($\gamma\beta$) of visible part ($D^{(*)}\mu$) along z axis is equal to proper velocity of B along this axis
- This gives $p_B(z)$, other components determined from knowledge of B flight direction
- Can then construct other rest-frame quantities (q^2, m^2_{miss}, E^*_μ)

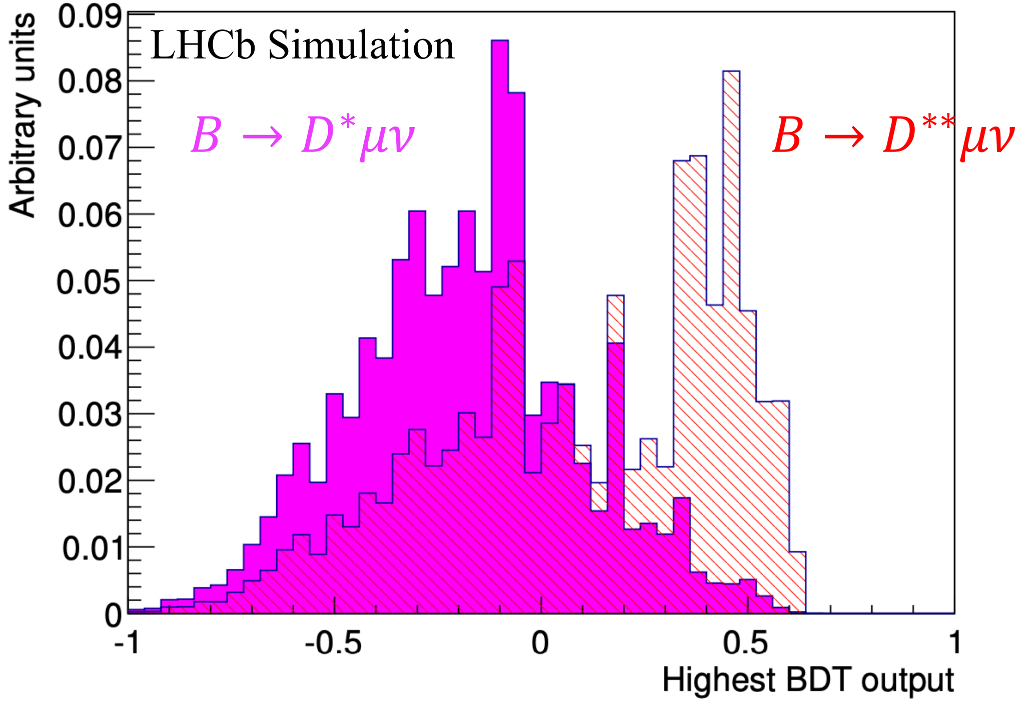


$$|p_B| = \frac{m_B}{m_{D^*\mu}} p_{D^*\mu}(z)\sqrt{1+\tan^2\alpha}$$

Track isolation

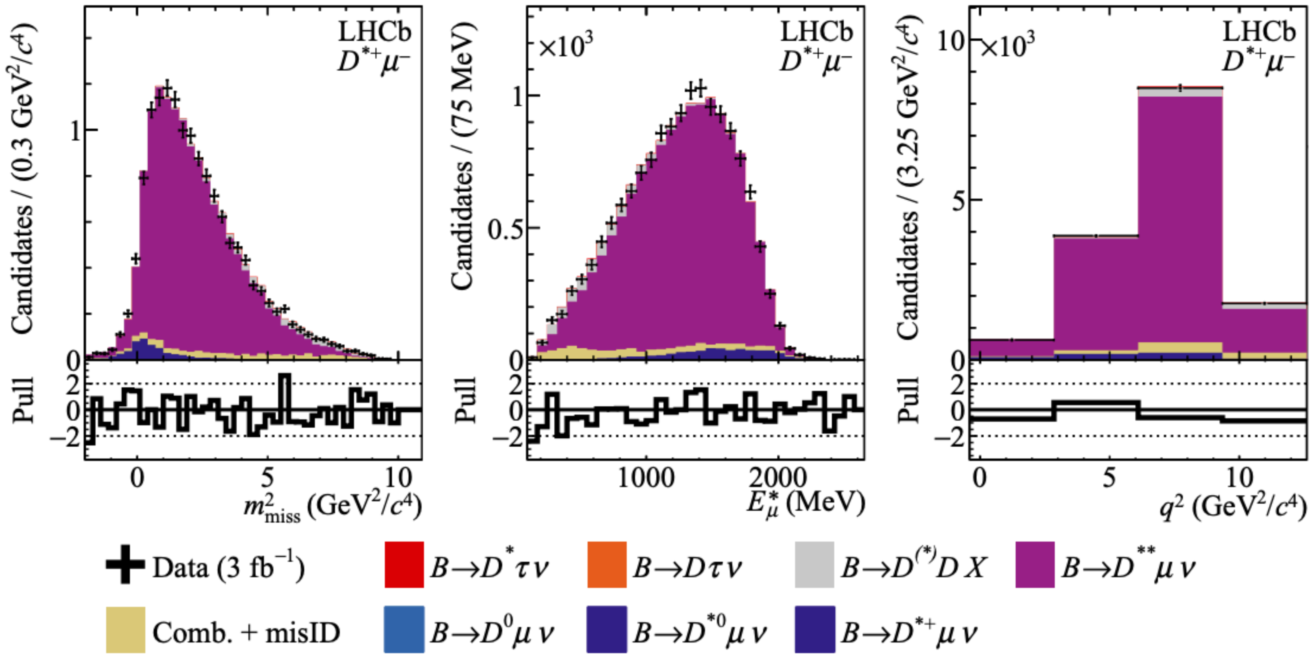
- Technique used to reject backgrounds with additional tracks
- Aim is to isolate signal candidate from the rest of the event
- BDT used to determine whether a track is compatible with a B vertex
- Efficient separation of $B \to D^{**}\mu\nu$ processes, which are very signal-like
- Can also invert the cut to obtain control sample with enriched backgrounds





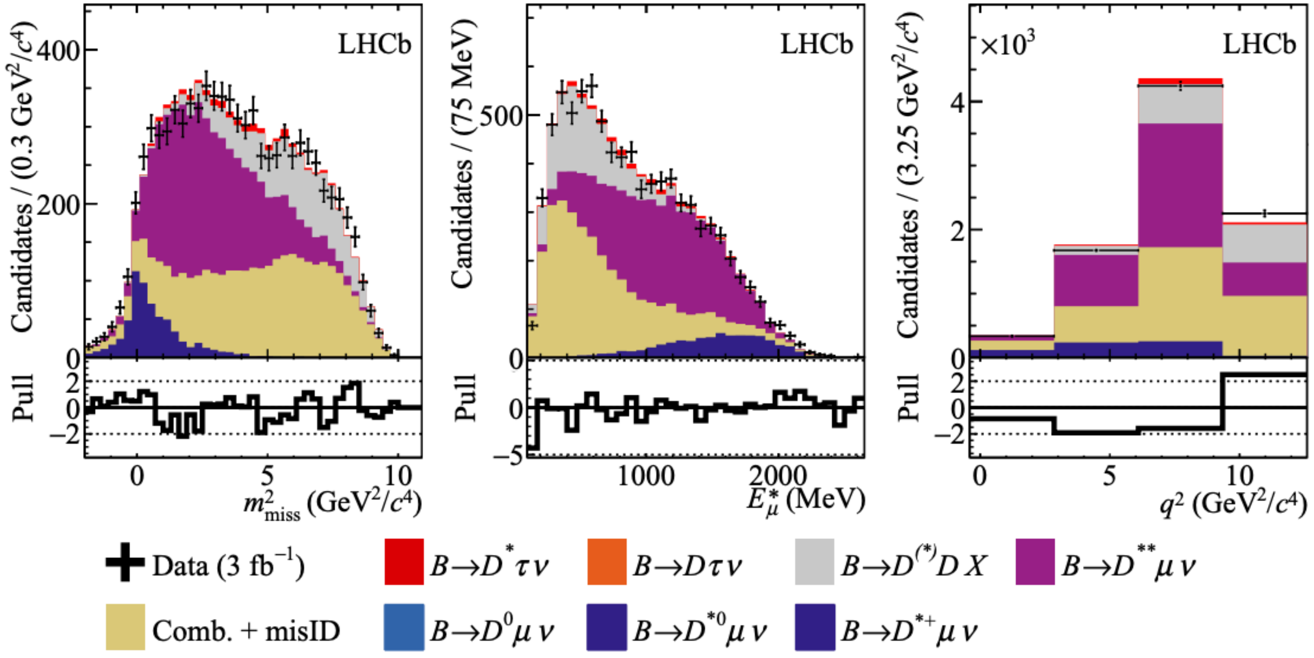
Control regions – one pion sample

- Sample requiring exactly one extra pion (of correct charge)
- This is used to model $B \to (D^{**} \to D^{*}\pi)l\nu$ backgrounds
- There are four known D^{**} resonances, their yields float individually
- Form factor model from Bernlochner & Ligeti [PRD 95 (2017) 014022], all parameters are unconstrained



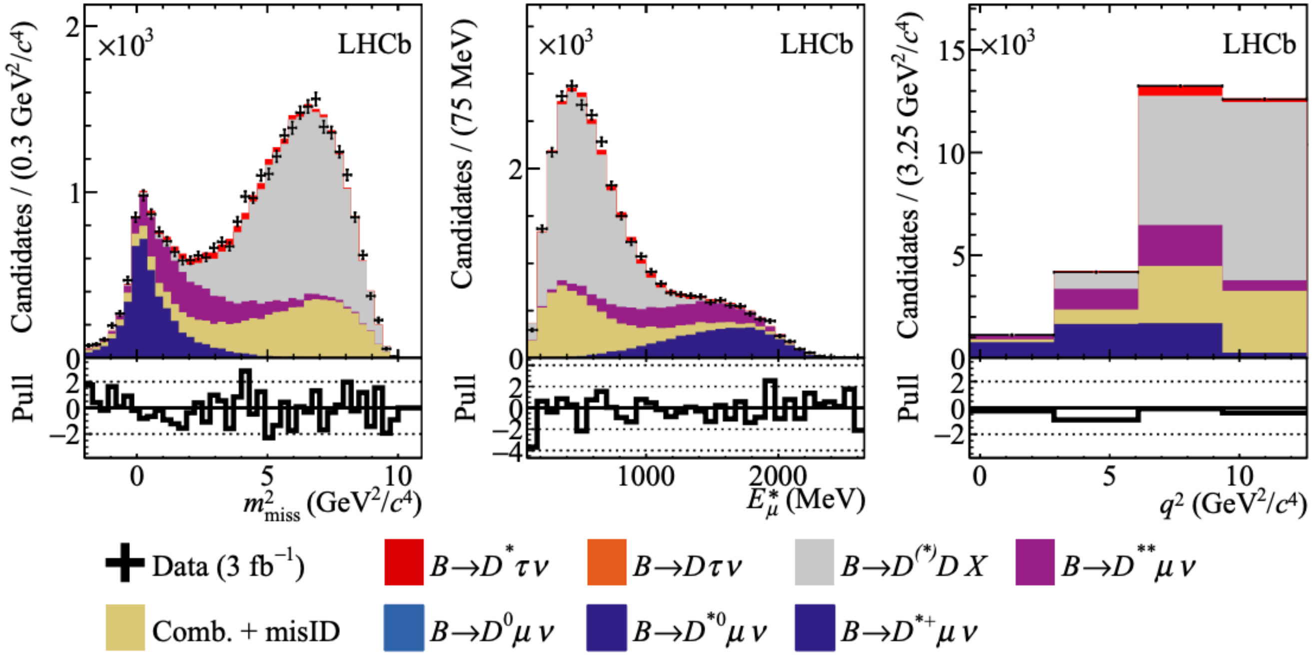
Control regions – two pion sample

- Sample requiring exactly two extra pions
- This is used to model $B \to (D^{**} \to D^{*}\pi\pi)l\nu$ backgrounds
- These are heavier D^{**} species
- Currently no form factor model for this, use a cocktail simulation sample



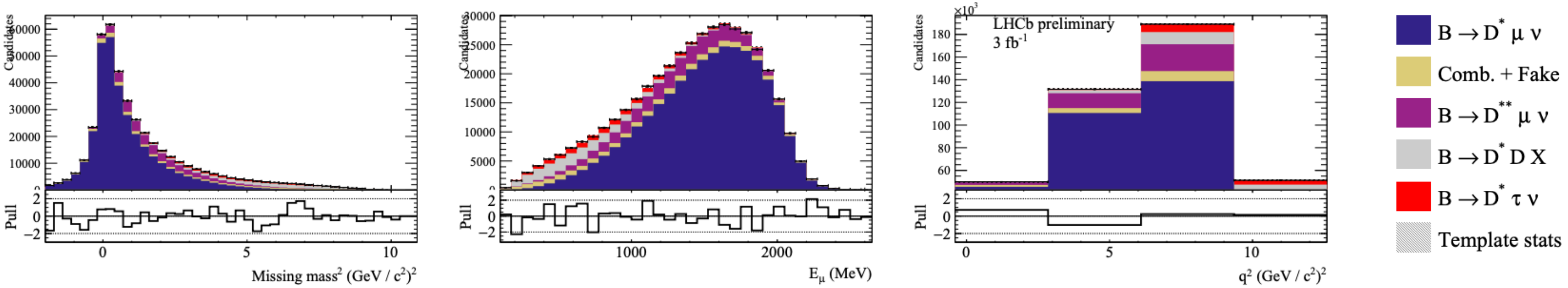
Control regions – kaon sample

- Sample requiring at least one extra kaon
- This models $B \rightarrow D^{(*)}DX$ backgrounds
- Float the mass combinations of $B \rightarrow DDKX$ and fraction of $B \rightarrow DDK^*$



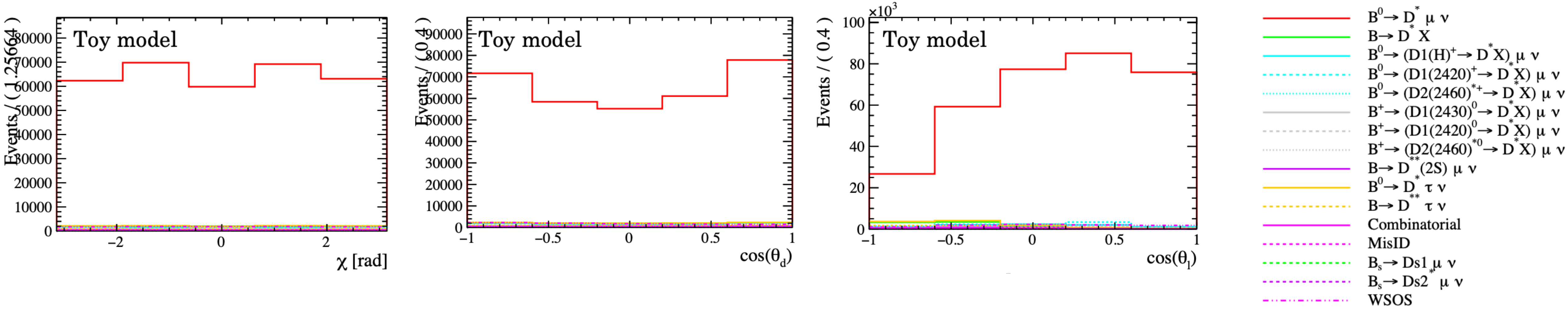
Comparison with previous result

- Previous measurement was only $R(D^*)$ with same data sample
- Refitted this sample, with updated procedure
- From this fit, obtain $R(D^*) = 0.293$, 1.6σ agreement with previous result



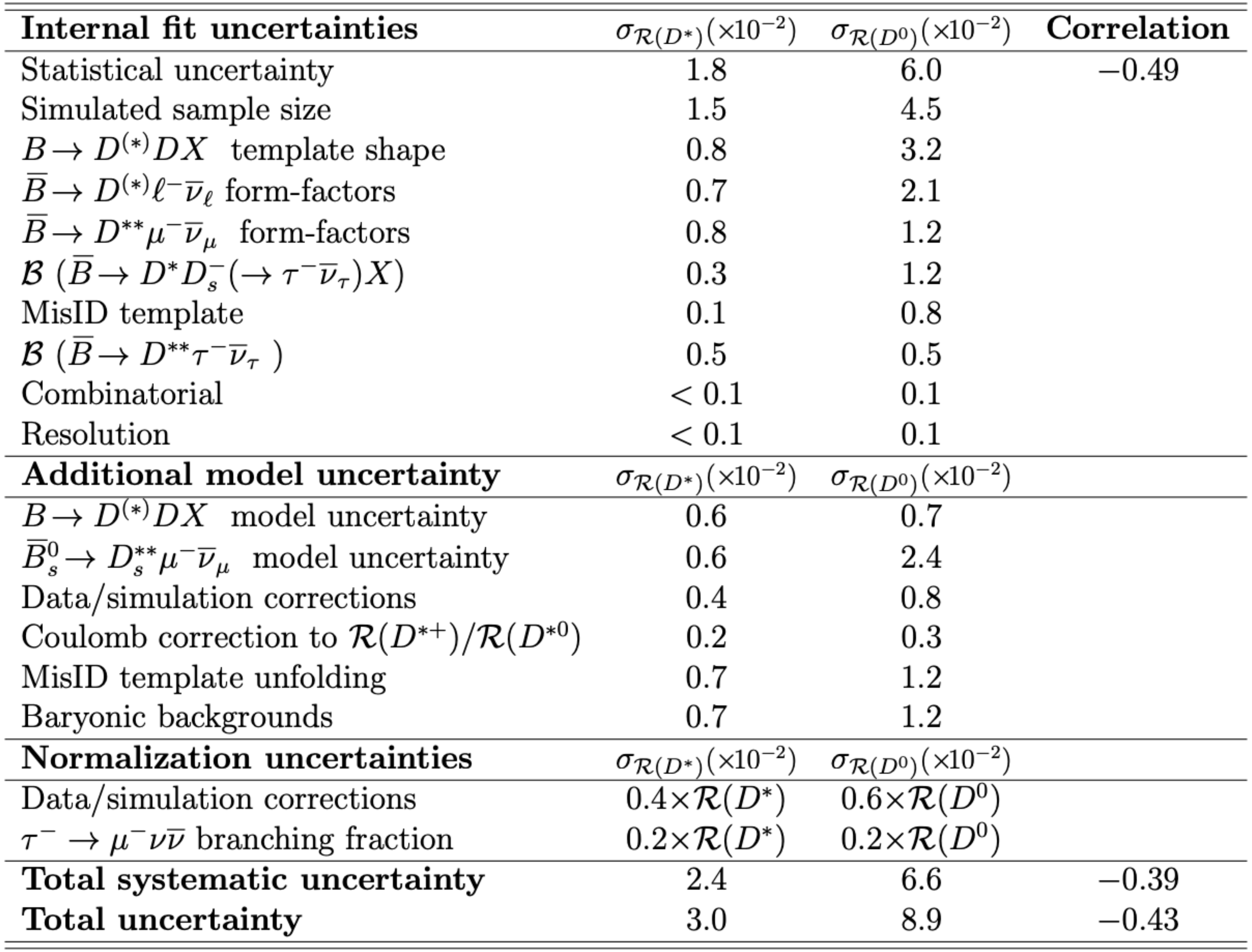
Fitting for Wilson Coefficients

- Use HAMMER package to reweight MC generated with SM decay model to NP scenarios
- Perform fits with CLN, BGL and BLPR parameterisations
- Statistical precision (Run 1 only) comparable to latest B-factory measurements (Phys. Rev. D 100, 052007 (2019), Phys. Rev. Lett. 123, 091801 (2019))



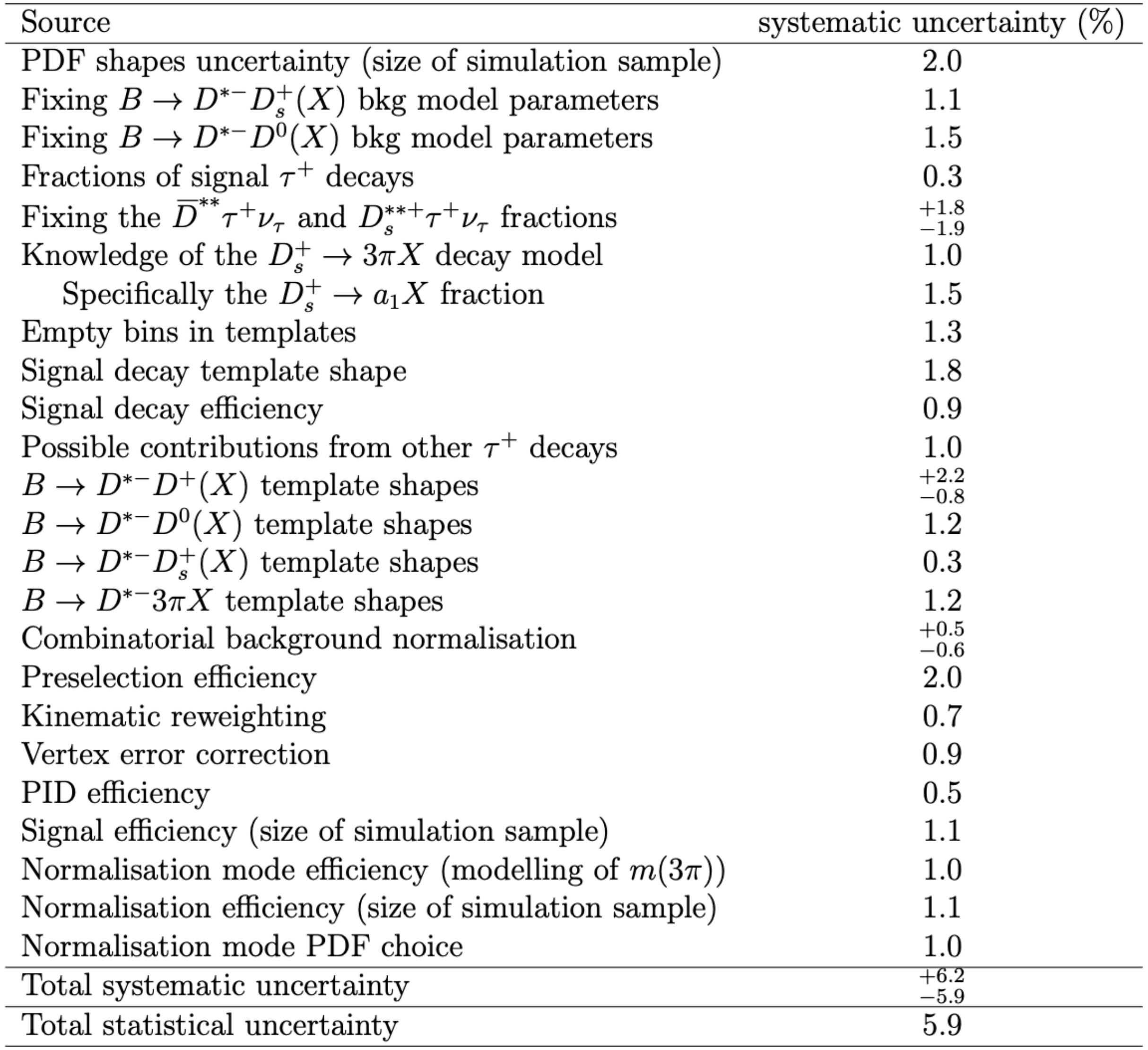
See: CERN-THESIS-2022-105

Systematics, $R(D^0) - R(D^*)$ muonic



Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	**Correlation**
Statistical uncertainty	1.8	6.0	−0.49
Simulated sample size	1.5	4.5	
$B \to D^{(*)}DX$ template shape	0.8	3.2	
$\overline{B} \to D^{(*)}\ell^-\overline{\nu}_\ell$ form-factors	0.7	2.1	
$\overline{B} \to D^{**}\mu^-\overline{\nu}_\mu$ form-factors	0.8	1.2	
$\mathcal{B}\ (\overline{B} \to D^* D_s^-(\to \tau^-\overline{\nu}_\tau)X)$	0.3	1.2	
MisID template	0.1	0.8	
$\mathcal{B}\ (\overline{B} \to D^{**}\tau^-\overline{\nu}_\tau)$	0.5	0.5	
Combinatorial	< 0.1	0.1	
Resolution	< 0.1	0.1	
Additional model uncertainty	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
$B \to D^{(*)}DX$ model uncertainty	0.6	0.7	
$\overline{B}_s^0 \to D_s^{**}\mu^-\overline{\nu}_\mu$ model uncertainty	0.6	2.4	
Data/simulation corrections	0.4	0.8	
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3	
MisID template unfolding	0.7	1.2	
Baryonic backgrounds	0.7	1.2	
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$	
Data/simulation corrections	$0.4 \times \mathcal{R}(D^*)$	$0.6 \times \mathcal{R}(D^0)$	
$\tau^- \to \mu^-\nu\overline{\nu}$ branching fraction	$0.2 \times \mathcal{R}(D^*)$	$0.2 \times \mathcal{R}(D^0)$	
Total systematic uncertainty	2.4	6.6	−0.39
Total uncertainty	3.0	8.9	−0.43

Systematics, $R(D^*)$ hadronic



Source	systematic uncertainty (%)
PDF shapes uncertainty (size of simulation sample)	2.0
Fixing $B \to D^{*-} D_s^+(X)$ bkg model parameters	1.1
Fixing $B \to D^{*-} D^0(X)$ bkg model parameters	1.5
Fractions of signal τ^+ decays	0.3
Fixing the $\overline{D}^{**}\tau^+\nu_\tau$ and $D_s^{**+}\tau^+\nu_\tau$ fractions	$^{+1.8}_{-1.9}$
Knowledge of the $D_s^+ \to 3\pi X$ decay model	1.0
Specifically the $D_s^+ \to a_1 X$ 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
$B \to D^{*-} D^+(X)$ template shapes	$^{+2.2}_{-0.8}$
$B \to D^{*-} D^0(X)$ template shapes	1.2
$B \to D^{*-} D_s^+(X)$ template shapes	0.3
$B \to D^{*-} 3\pi X$ 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

LFU in $b \to sll$

- At LHCb, test LFU in electron and muon modes by measuring:

$$R\left(K^{(*)}\right) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

- Measure ratios normalised to $B \to J/\psi K^{(*)}$ to control efficiencies, and cancel systematics
- Have to correct for electron energy loss in the detector via Bremsstrahlung processes
- Make measurements in regions of q^2
  - ″Low″: [0.1 – 1.1] GeV^2
  - ″Central″: [1.1 – 6.0] GeV^2

LFU in $b \to sll$

[arXiv:2212.09152, arXiv:2212.09153]
Submitted to PRL, PRD

- New result measures $R(K)$ and $R(K^*)$ consistent with SM (agree within 1σ)
- This supersedes previous result [Nature Physics 18, 277–282 (2022)]
- Main changes are due to misidentified hadronic background
  - Improved modelling
  - Tighter particle identification criteria for electrons