LFU tests in $b \to c l \nu$ decays at LHCb

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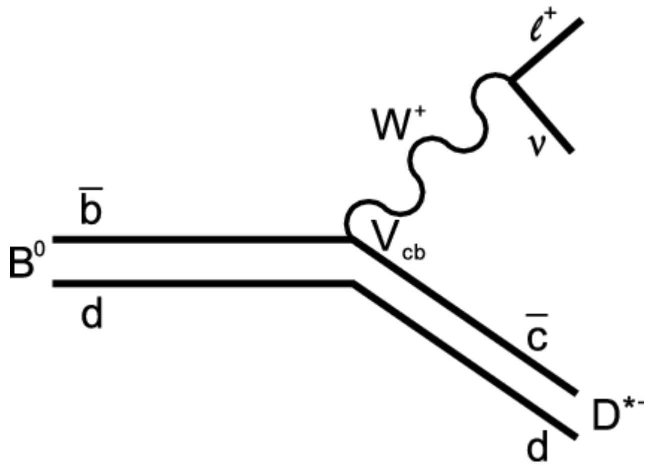
Outline

- $R(D^*)$ measurement with muonic τ decay
- $R(D^*)$ measurement with hadronic τ decay
- Future measurements



$R(D^*)$ measurements at LHCb

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

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

$R(D^*)$ measurements at LHCb

Previous measurements

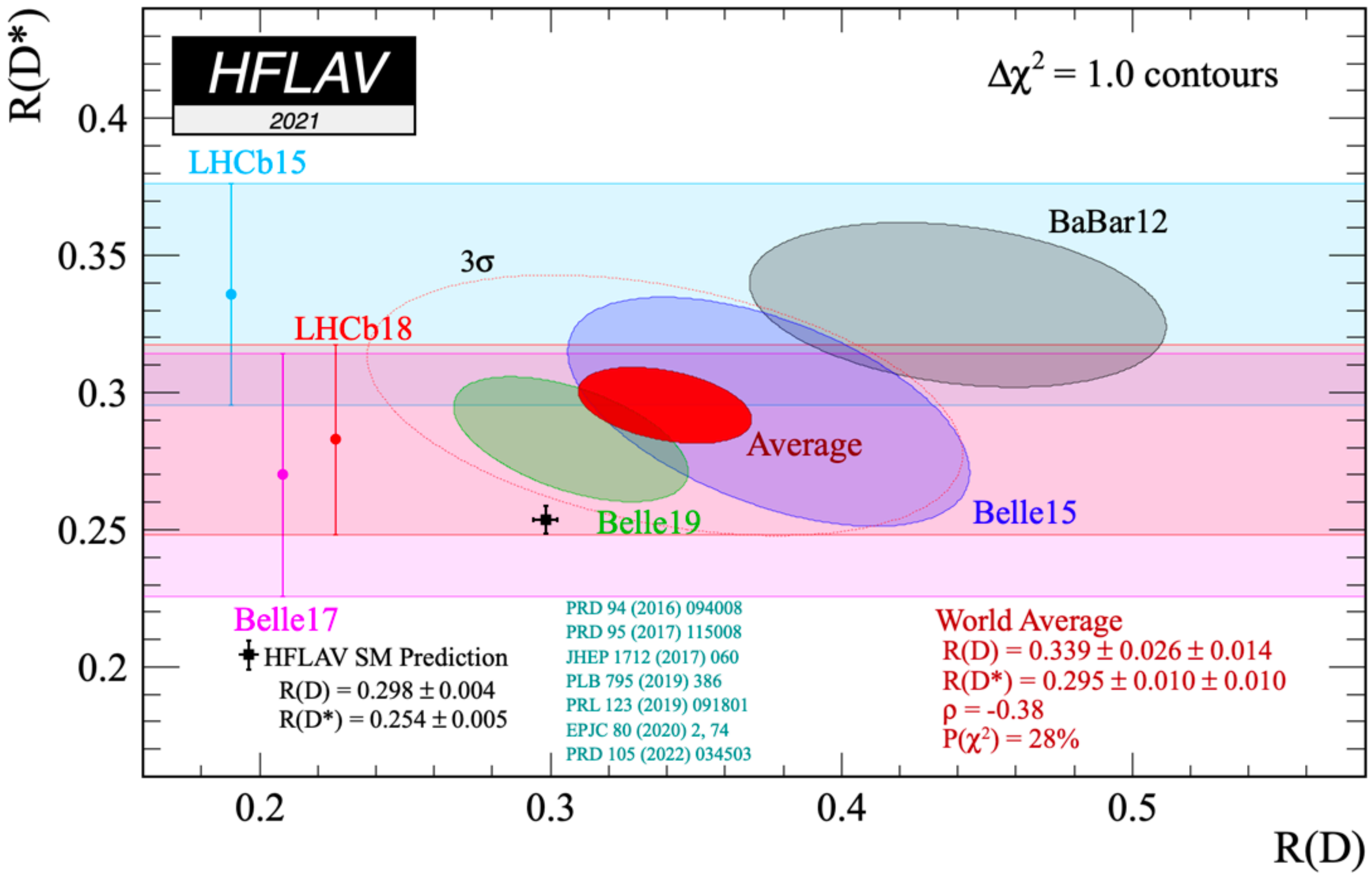
- $R(D^*)$ muonic, Run 1 data [Phys. Rev. Lett. 115, 111803 (2015)]
- $R(D^*)$ hadronic, Run 1 data [Phys. Rev. Lett. 120, 171802 (2018)]

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

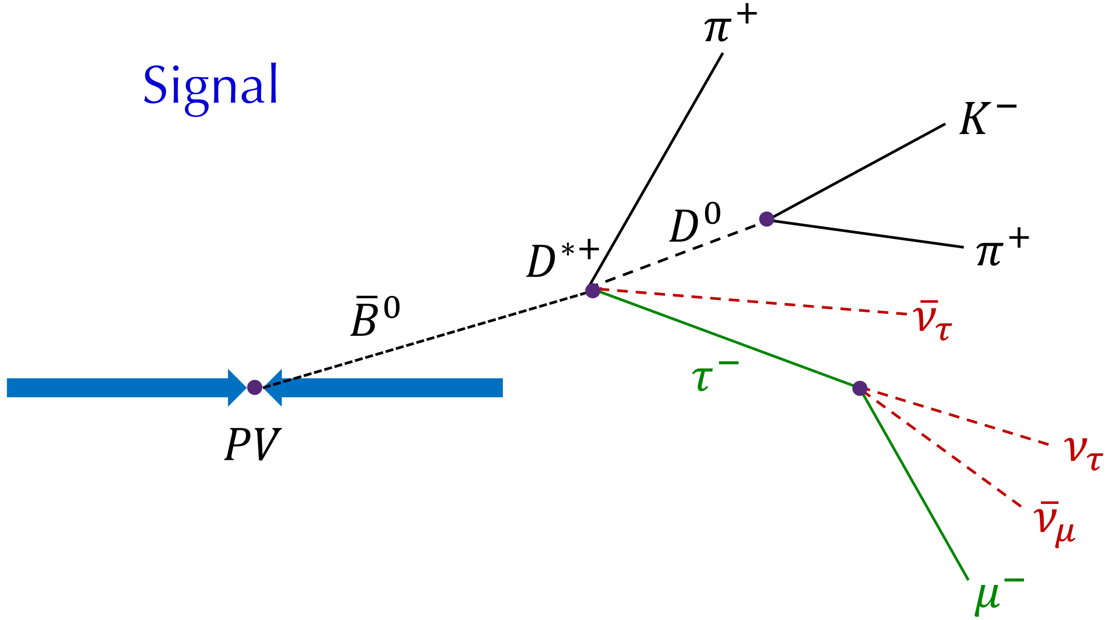
Combined measurement of R(D^0) and R(D^*)

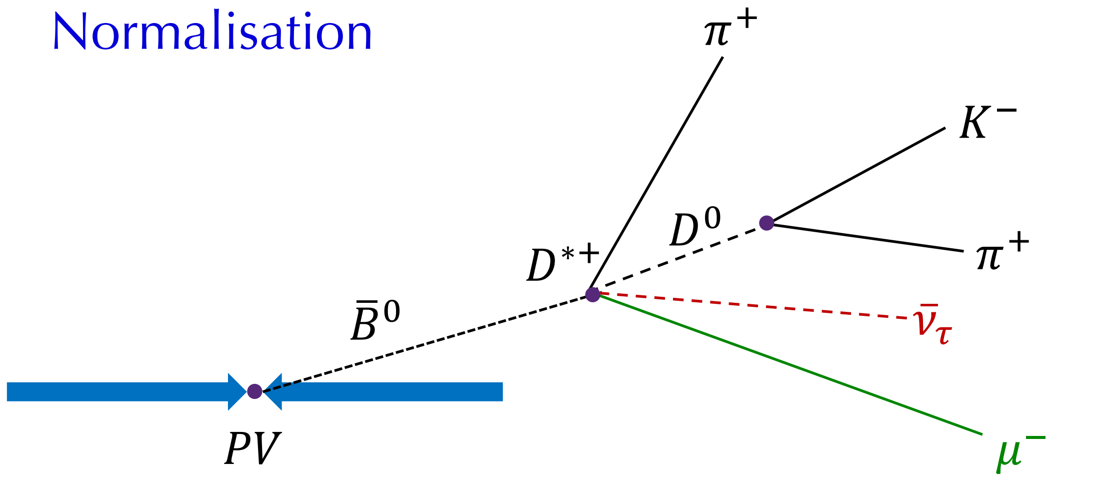
LHCB-PAPER-2022-039

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

LHCB-PAPER-2022-039

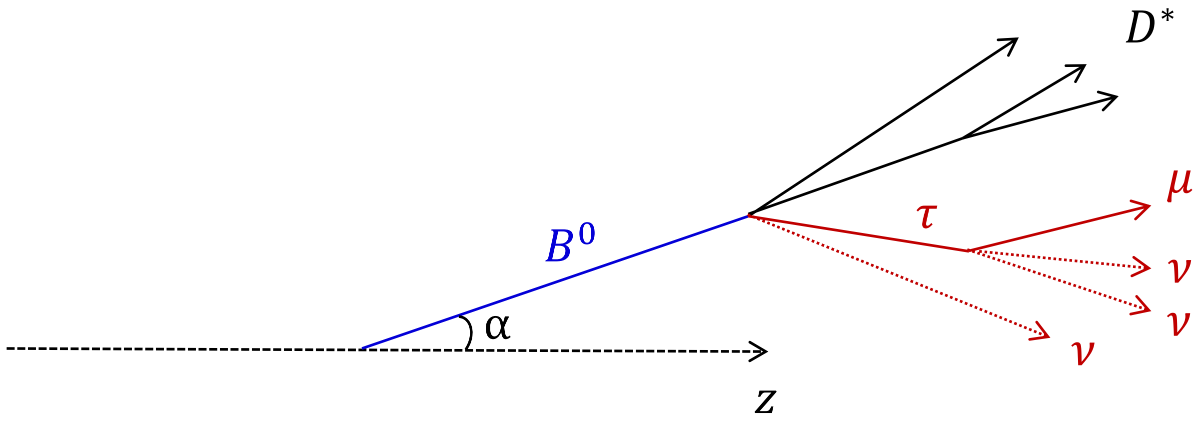
- Uses Run 1 LHCb data (3 fb^{-1})
- Muonic τ decay has large branching fraction (17.4%)
- Make measurement of R(D^0) and R(D^*) using the same dataset
- Split dataset into two samples:
  - $\{D^0\mu\}$ - Veto $D^{*+} \to D^0\pi^+$
  - $\{D^*\mu\}$ - Combine D^0 with slow pion
- $\{D^0\mu\}$ ~5 times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





Kinematic reconstruction

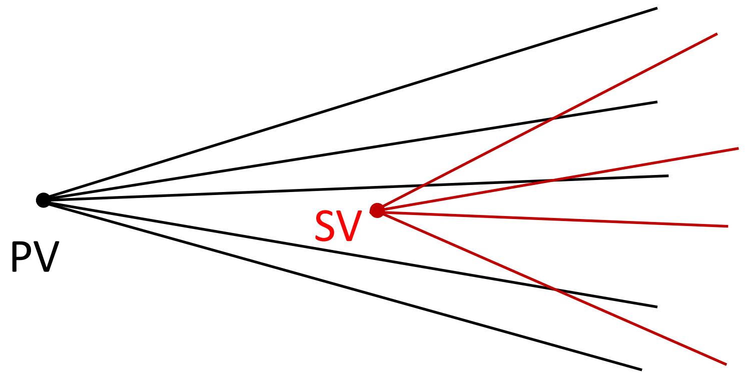
- Missing neutrinos create an experimental challenge, can't fit a clean mass peak
- Can't reconstruct $B\bar{B}$ rest frame at a hadron collider, so need to estimate B momentum
- Assume proper velocity ($\gamma\beta$) of visible part ($D^{(*)}\mu$) along z axis is equal to proper velocity of B along 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)

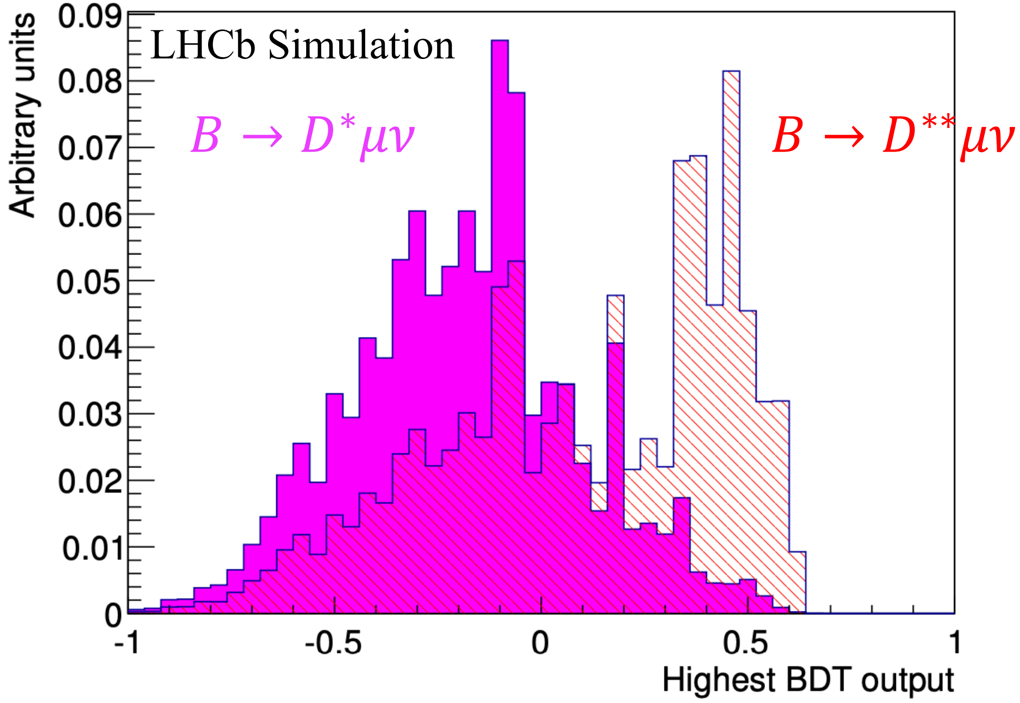


$$|p_B| = \frac{m_B}{m_{D^*\mu}} p_{D^*\mu}(z)\sqrt{1+\tan^2\alpha}$$

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

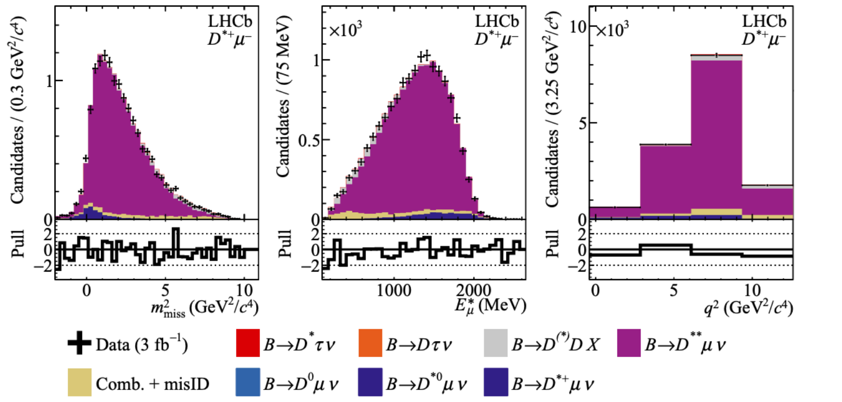




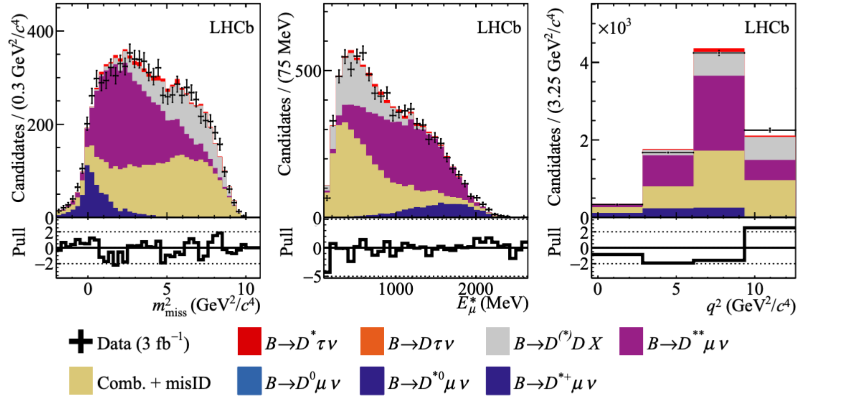
Control regions

Use 3 separate control regions:

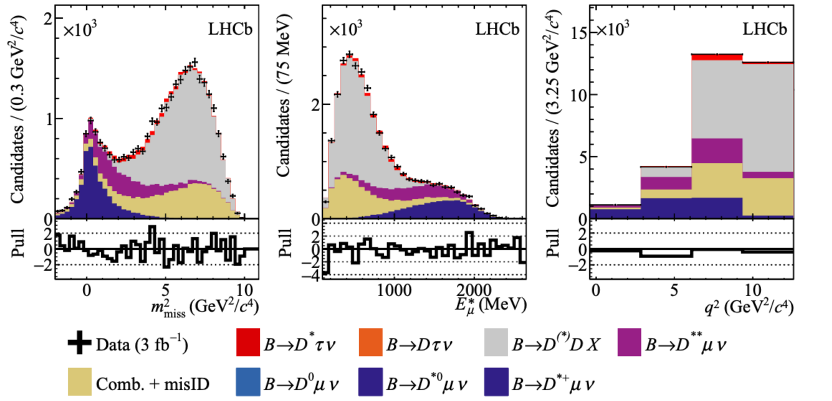
$B \rightarrow (D^{**} \rightarrow D^{*}\pi)l\nu$ - "One pion sample"



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

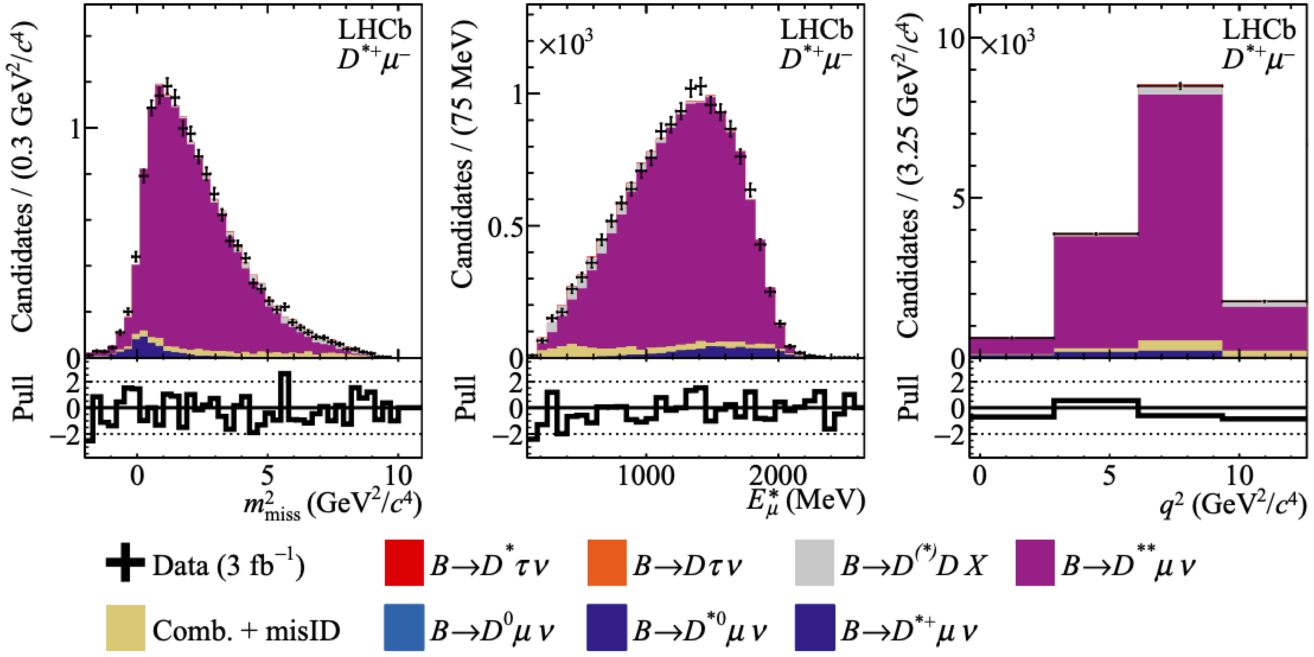


$B \rightarrow D^{(*)}DX$- "Kaon sample"



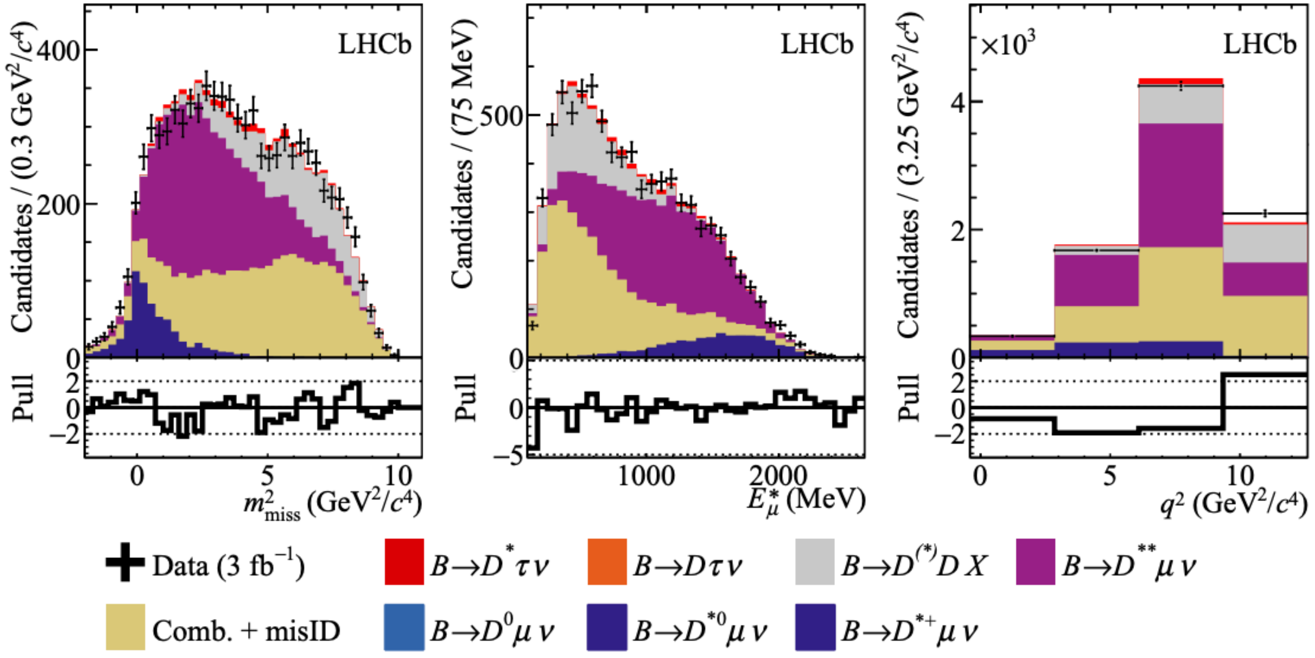
Control regions – one pion sample

- 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



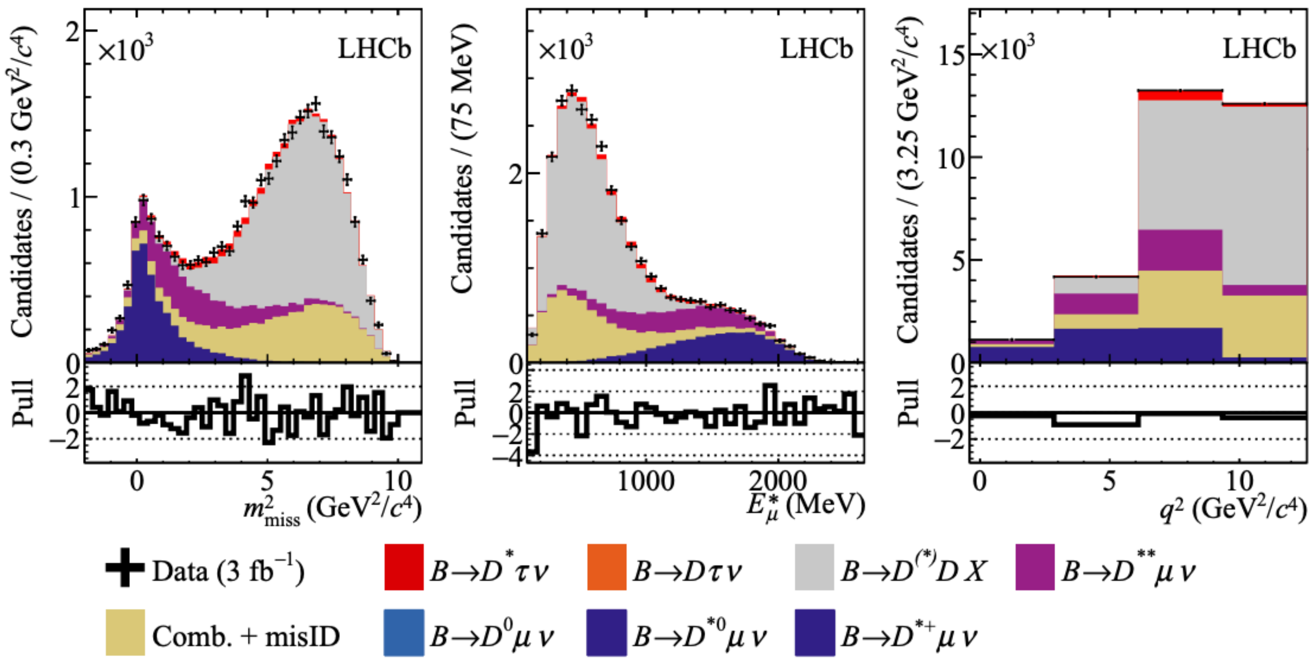
Control regions – two pion sample

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



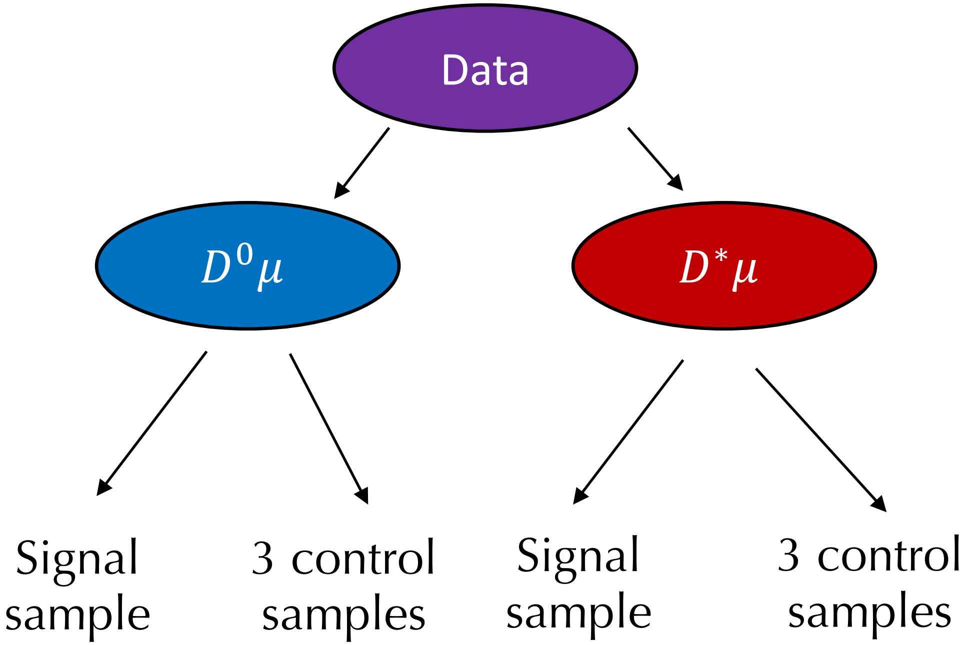
Control regions – kaon sample

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



Fit strategy

- 3D template fit in q^2, m^2_{miss}, E^*_l
- 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.

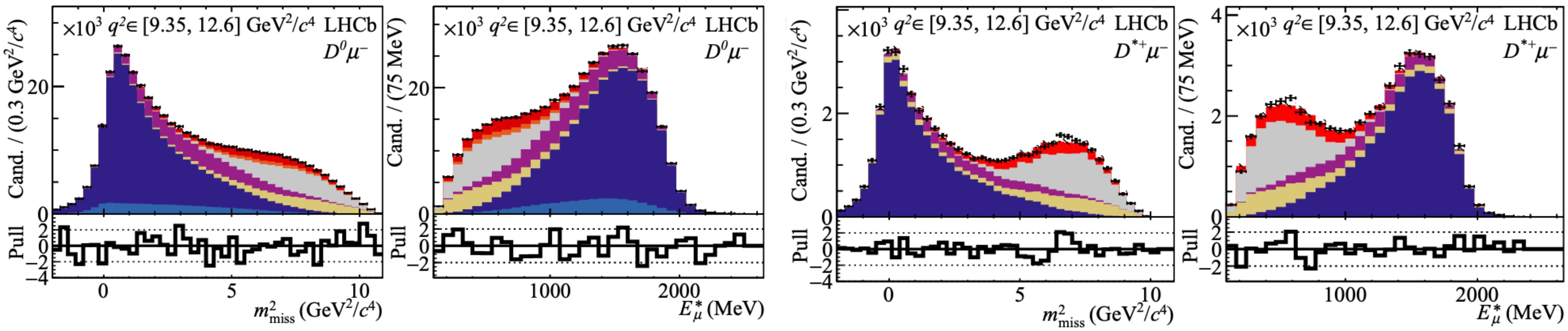


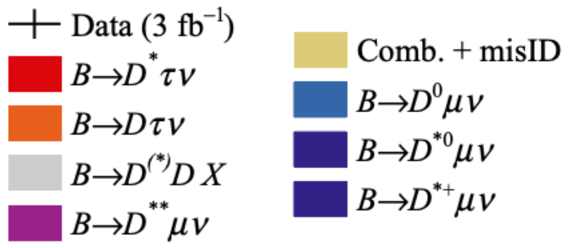
Fit projections

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

$D^0\mu$ sample

$D^*\mu$ sample





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

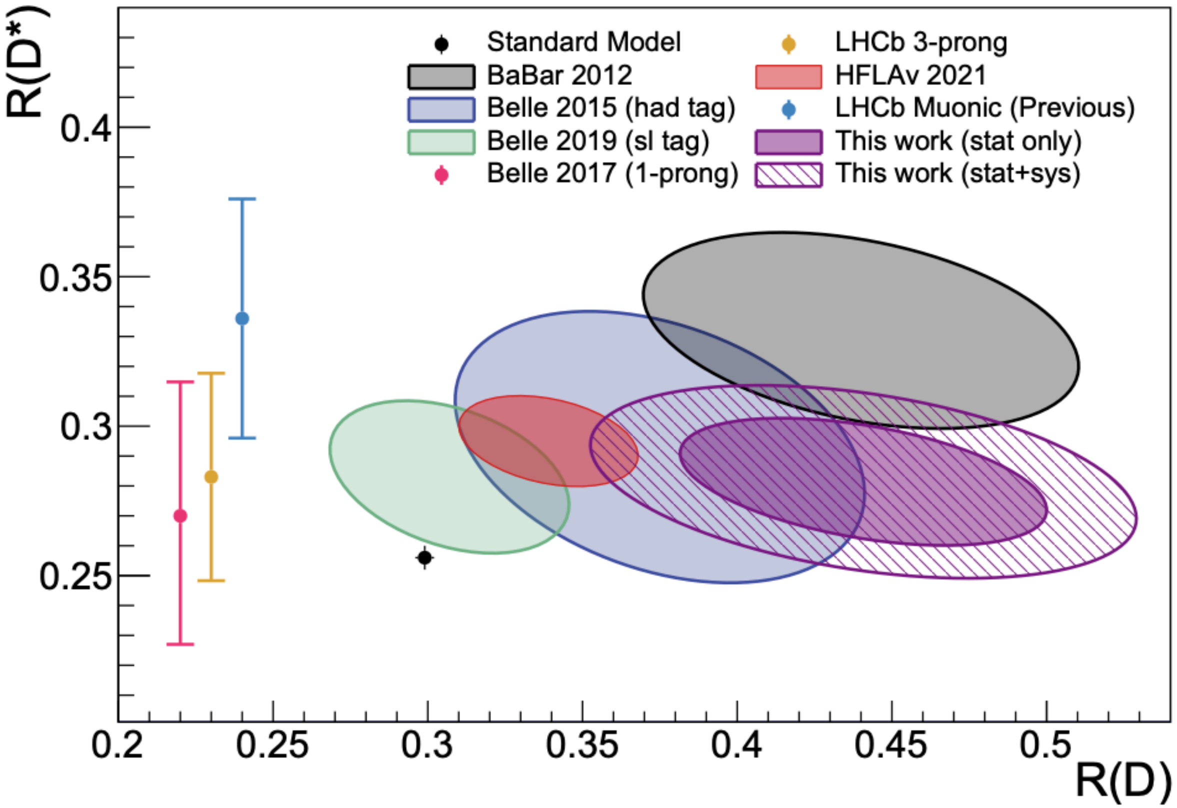
$\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu = 324\text{k}$

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 ($B \to D^* DX$ and $B \to D^{**}\mu\nu$)



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

Measure:

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

From simulation

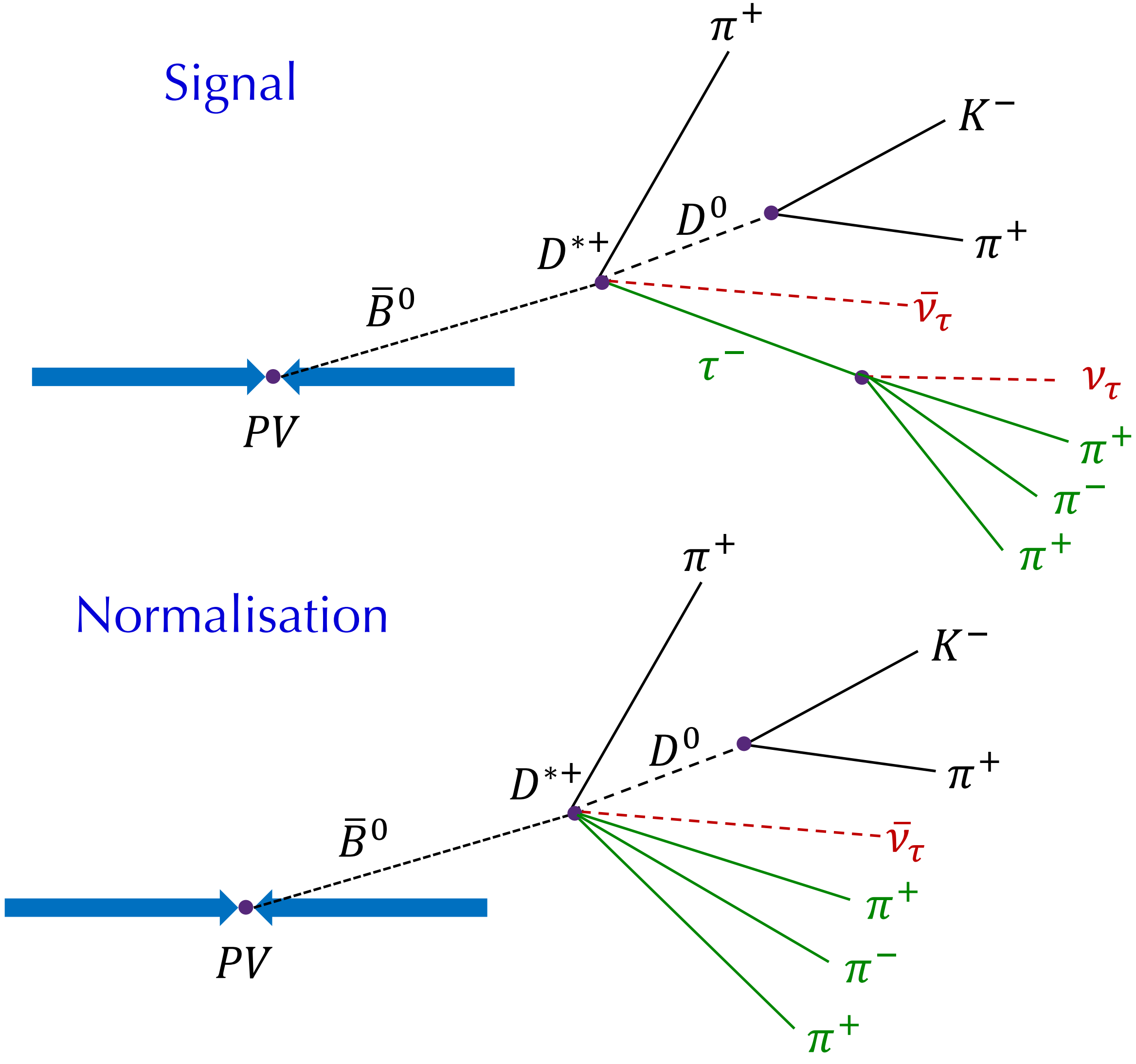
$$\kappa(D^*) = \frac{N_{sig}}{N_{norm}} \frac{\epsilon_{norm}}{\epsilon_{sig}} \left\{ \frac{1}{\mathcal{B}(\tau^+ \to 3\pi\bar{\nu}_\tau) + \mathcal{B}(\tau^+ \to 3\pi\pi^0\bar{\nu}_\tau)} \right\}$$

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

External branching fraction input [PDG]

R(D^*) hadronic

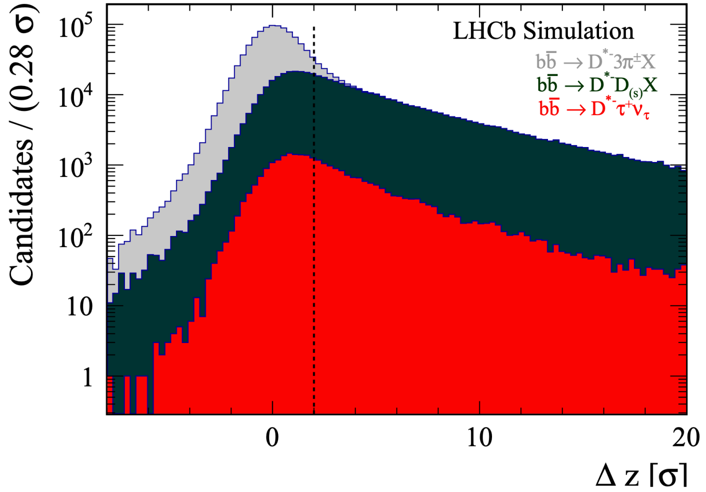
- ~40% more candidates than previous work (higher energy, better trigger)
- No muonic background, but large background from $\bar{B}^0 \to D^{*+} 3\pi X$
- Also large double charm background ($B \to D^* D X$)
- $\tau \to 3\pi(\pi^0)$ decay has branching fraction of 13.5%

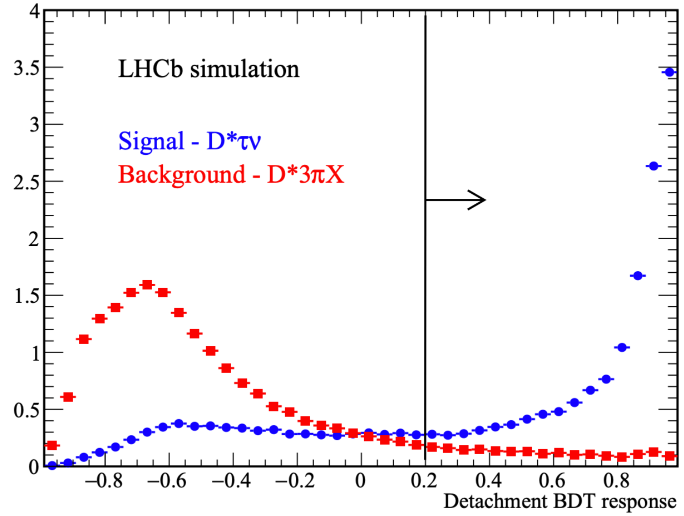


$B \to D^{*}3\pi X$ background

- 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

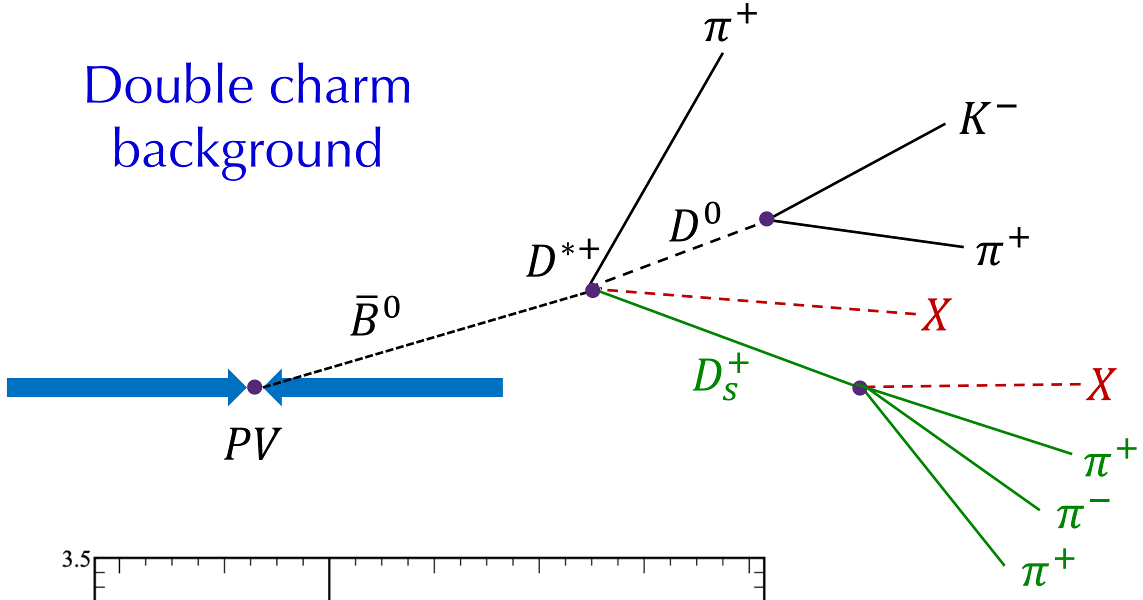
$$\Delta(z) = z(3\pi) - z(B^0)$$

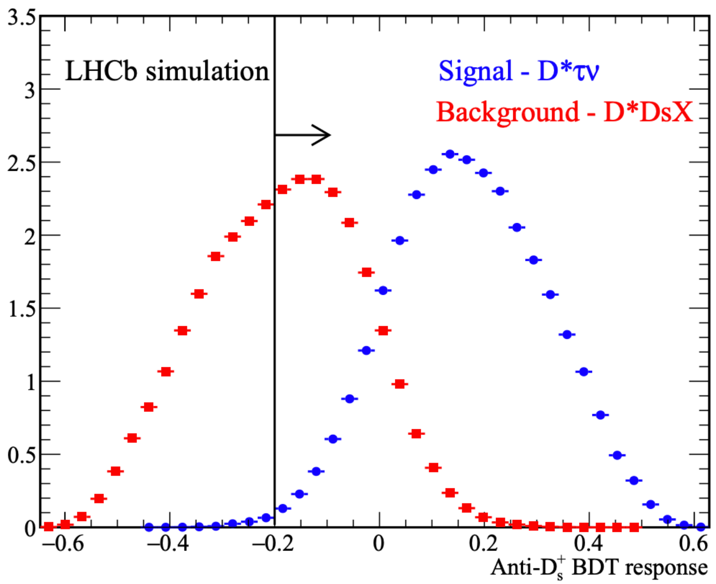




Double charm background

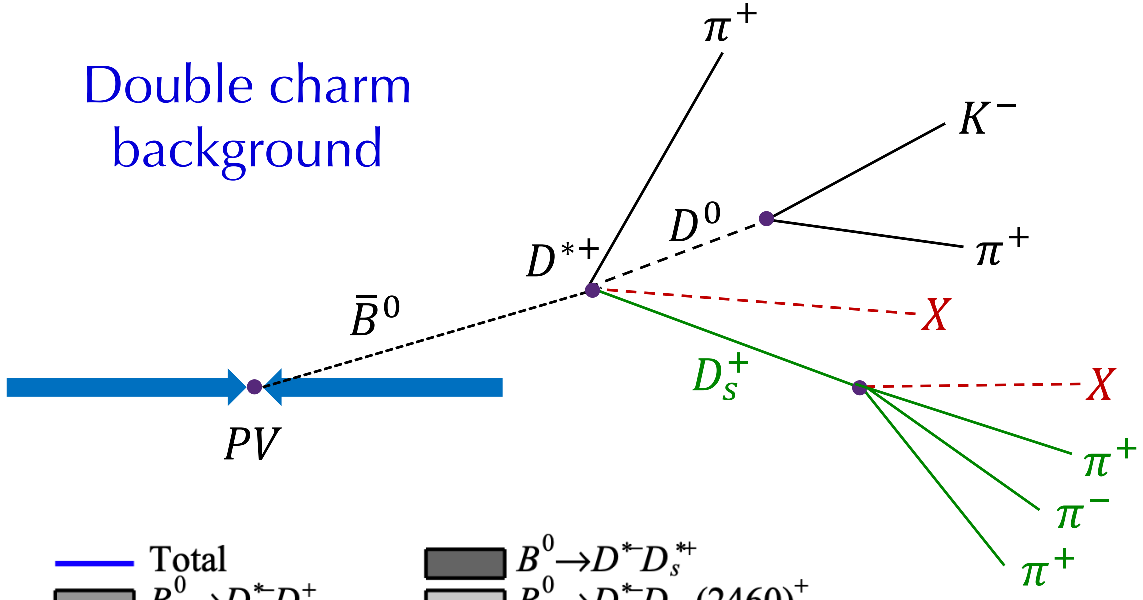
- Another large background comes from $B \to D^{*-} D_s^+ (\to 3\pi X) X$ events
- Most abundant background after full selection
- These can mimic the signal topology
- Train "anti-D_s^+" BDT to reject these decays
- Use isolation and kinematic variables in training
- The BDT is also used as a fit variable

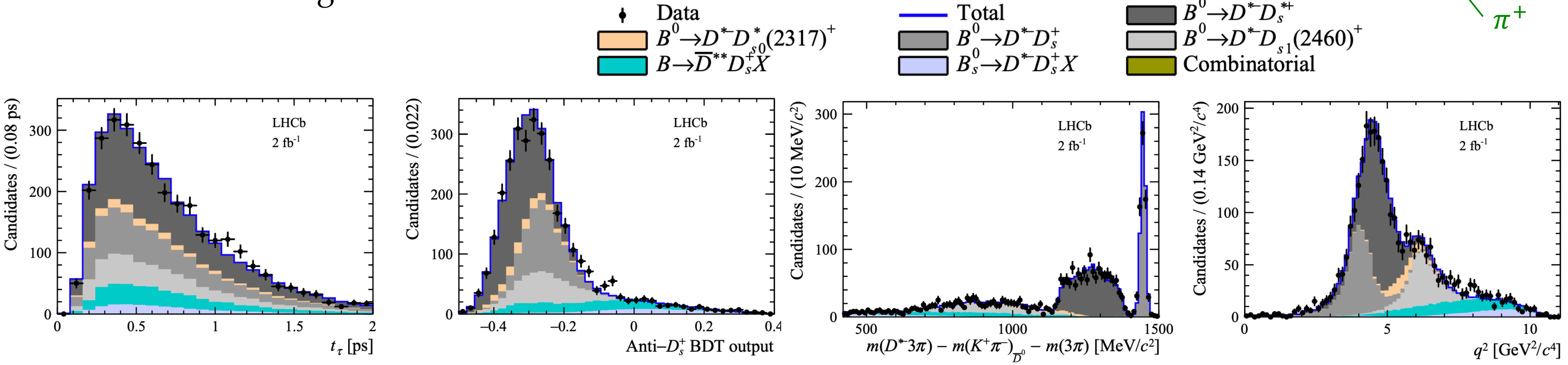




Double charm background

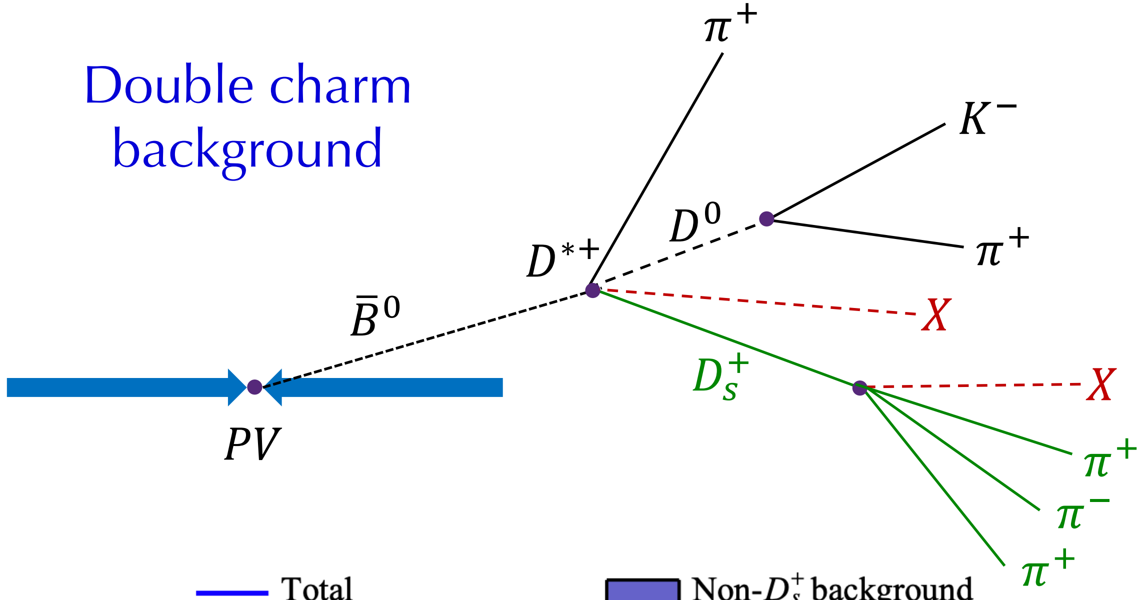
- Another large background comes from $B \to D^{*-} D_s^+(\to 3\pi X)X$ events
- Most abundant background after full selection
- Measure production fractions of these decays in separate fit, then use this to constrain signal fit

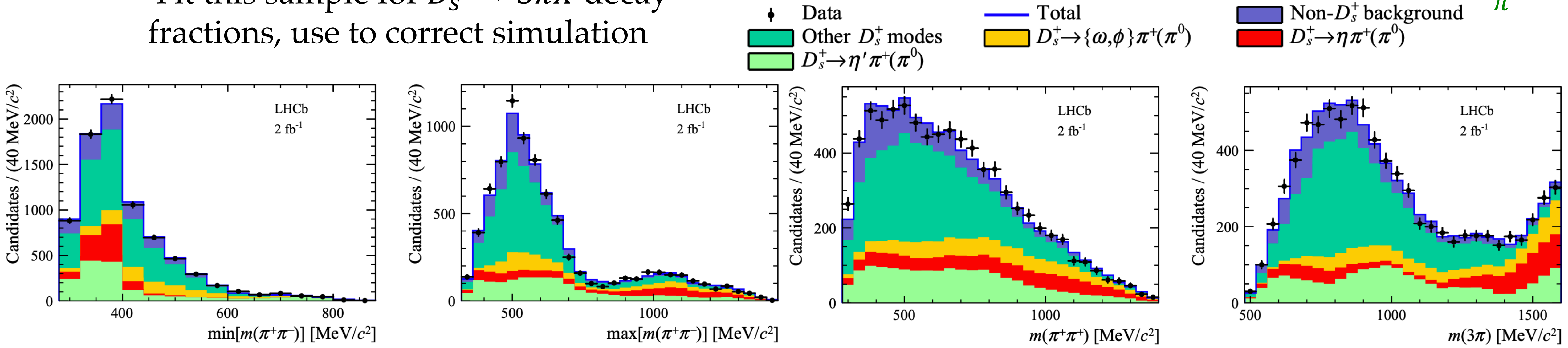




Double charm background

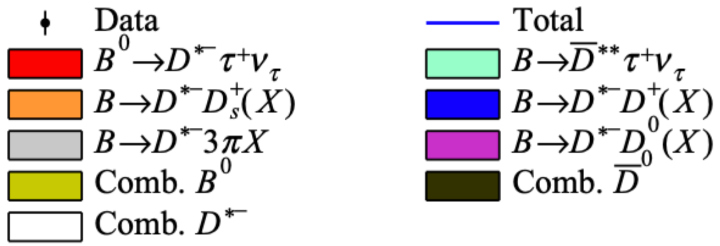
- Another large background comes from $B \to D^{*-} D_s^+ (\to 3\pi X) X$ events
- Most abundant background after full selection
- Can invert the cut on the anti-D_s^+ BDT to obtain control sample in data
- Fit this sample for $D_s^+ \to 3\pi X$ decay fractions, use to correct simulation





Fit strategy

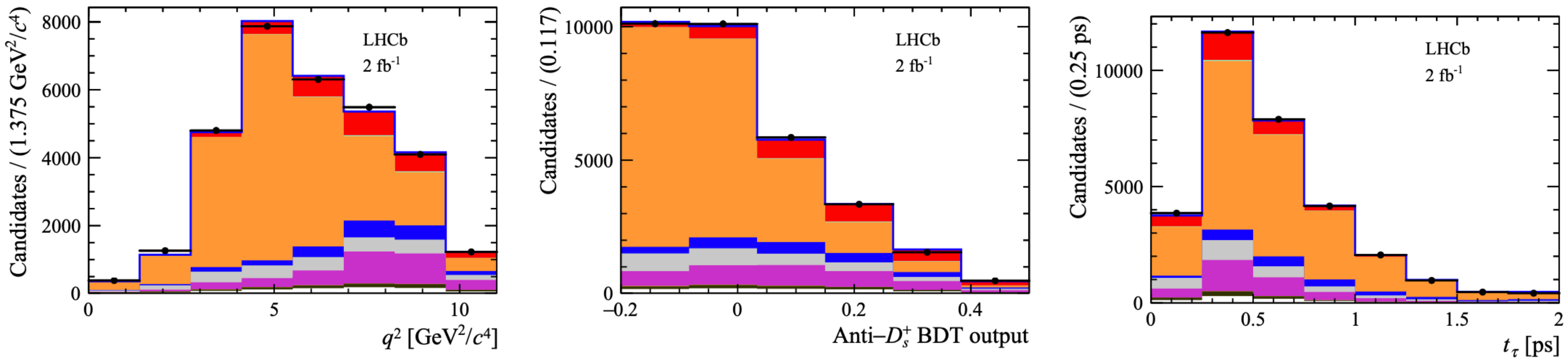
- 3D maximum likelihood template fit, using: $\{q^2$, anti-D_s^+ BDT, τ lifetime$\}$
- 8 bins in q^2 and τ lifetime, 6 bins in BDT output
- This fit is used to extract $B^0 \to D^{*-}\tau^+\nu_\tau$ yield
- $B^0 \to D^{*-}3\pi$ yield obtained from separate normalisation fit



Signal fit

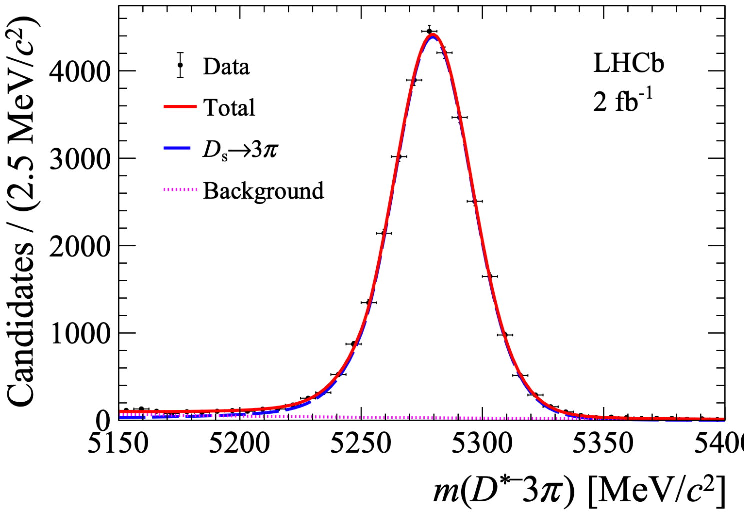
Yield = 2469 ± 154

(Run 1 yield = 1296 ± 86)



Normalisation fit

Yield ~ 30k



Result

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

Main systematic uncertainties are template sizes, preselection efficiency and signal template shape

This gives absolute branching fraction:

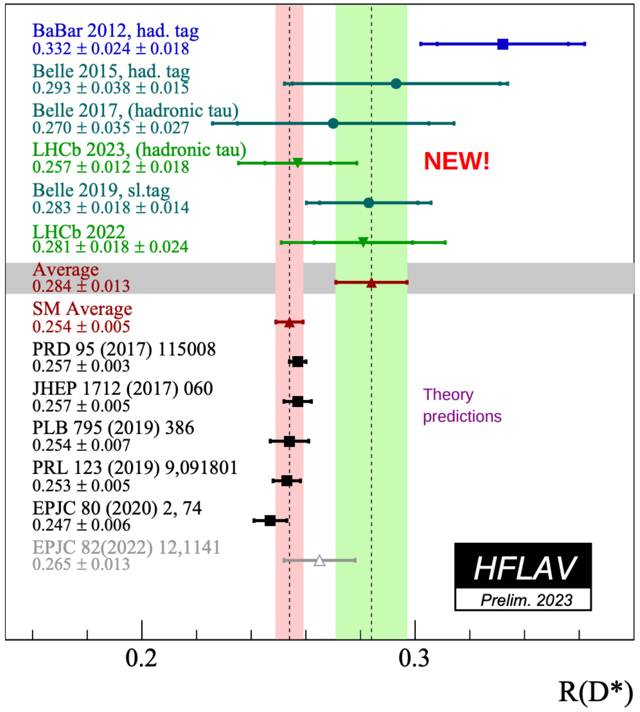
$$\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau) = \left(1.23 \pm 0.07\ (stat) \pm 0.08\ (syst) \pm 0.05\ (ext)\right) \times 10^{-2}$$

From this analysis:

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

Combining with previous (Run 1) result:

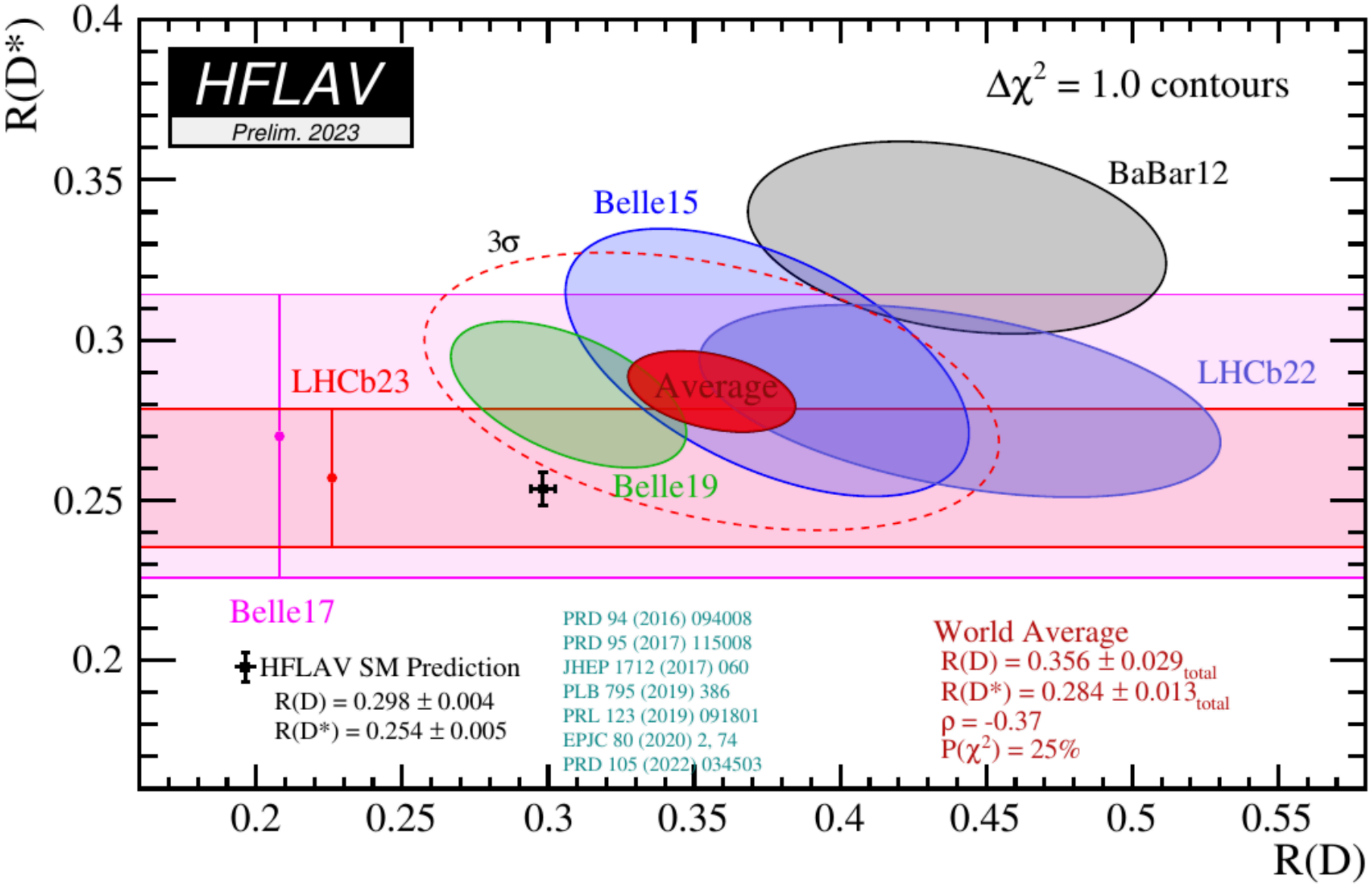
$$R(D^*) = 0.257 \pm 0.012\ (stat) \pm 0.014\ (syst) \pm 0.012\ (ext)$$



Consistent with SM within 1σ

Updated world average

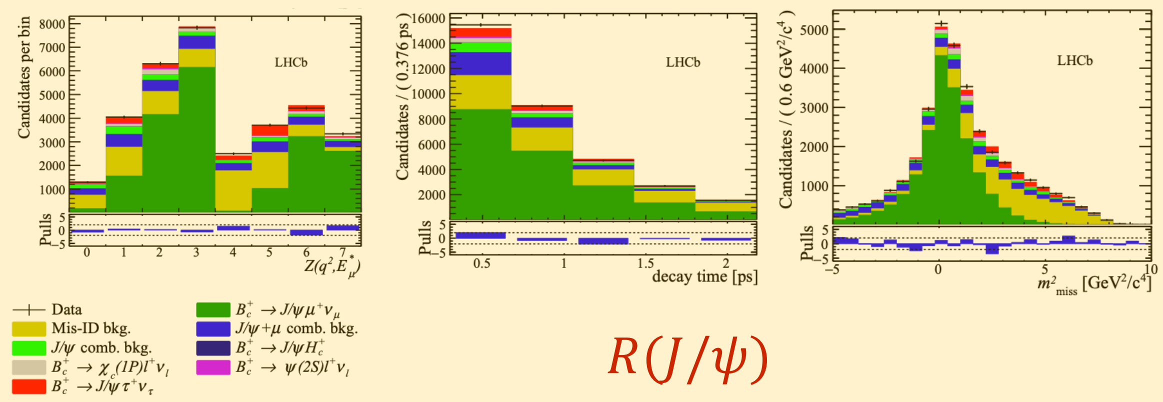
- With two new results (LHCb22, LHCb23), world average becomes:
  - $\boldsymbol{R(D^*) = 0.284 \pm 0.013}$
  - $\boldsymbol{R(D) = 0.356 \pm 0.029}$
- Deviation from SM for combined $R(D) - R(D^*)$ moves from $\mathbf{3.3\sigma}$ to $\mathbf{3.2\sigma}$ with the two new results



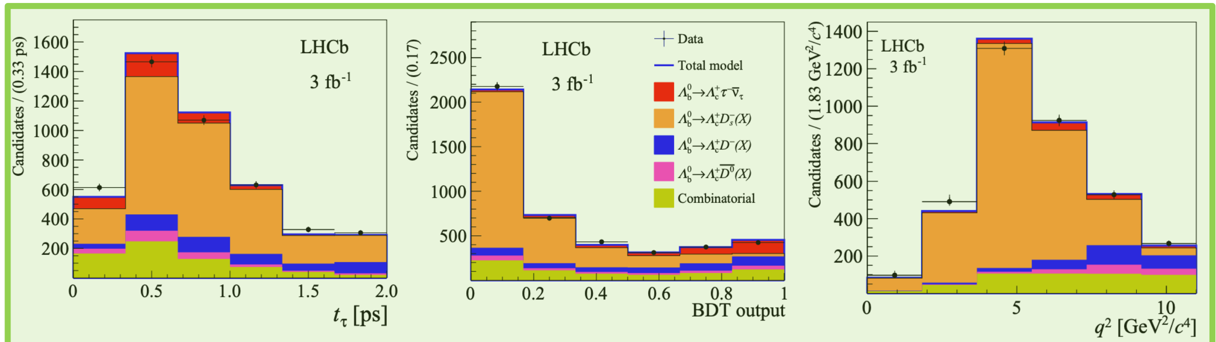
From HFLAV

Other measurements

Many other $R(H_c)$ being studied…

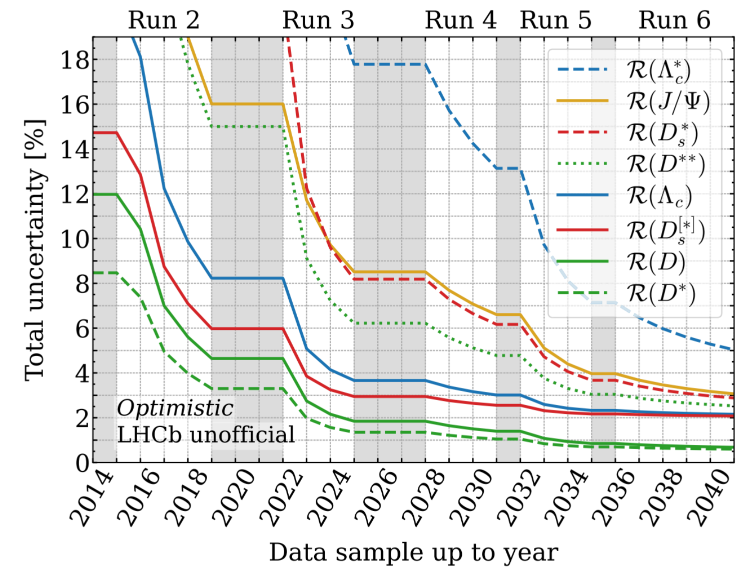


Phys. Rev. Lett. 120 (2018) 121801



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

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



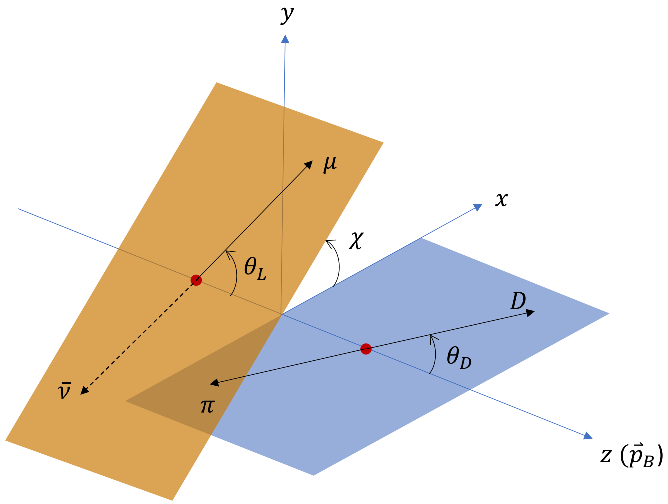
[Rev. Mod. Phys. 94, 015003 (2022)]

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:

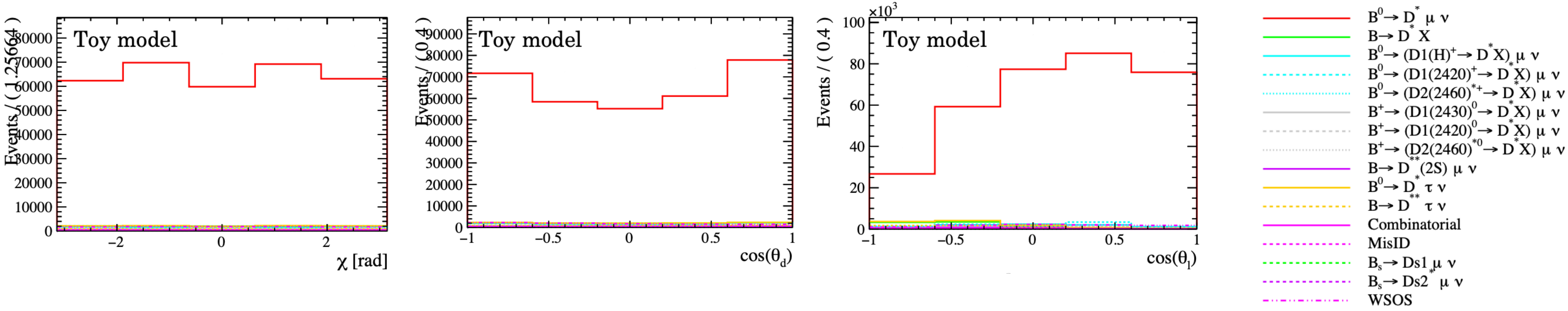
1. Fit directly for Wilson Coefficients, assuming a particular FF parameterisation
2. Measure angular coefficients with a model independent method

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



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))

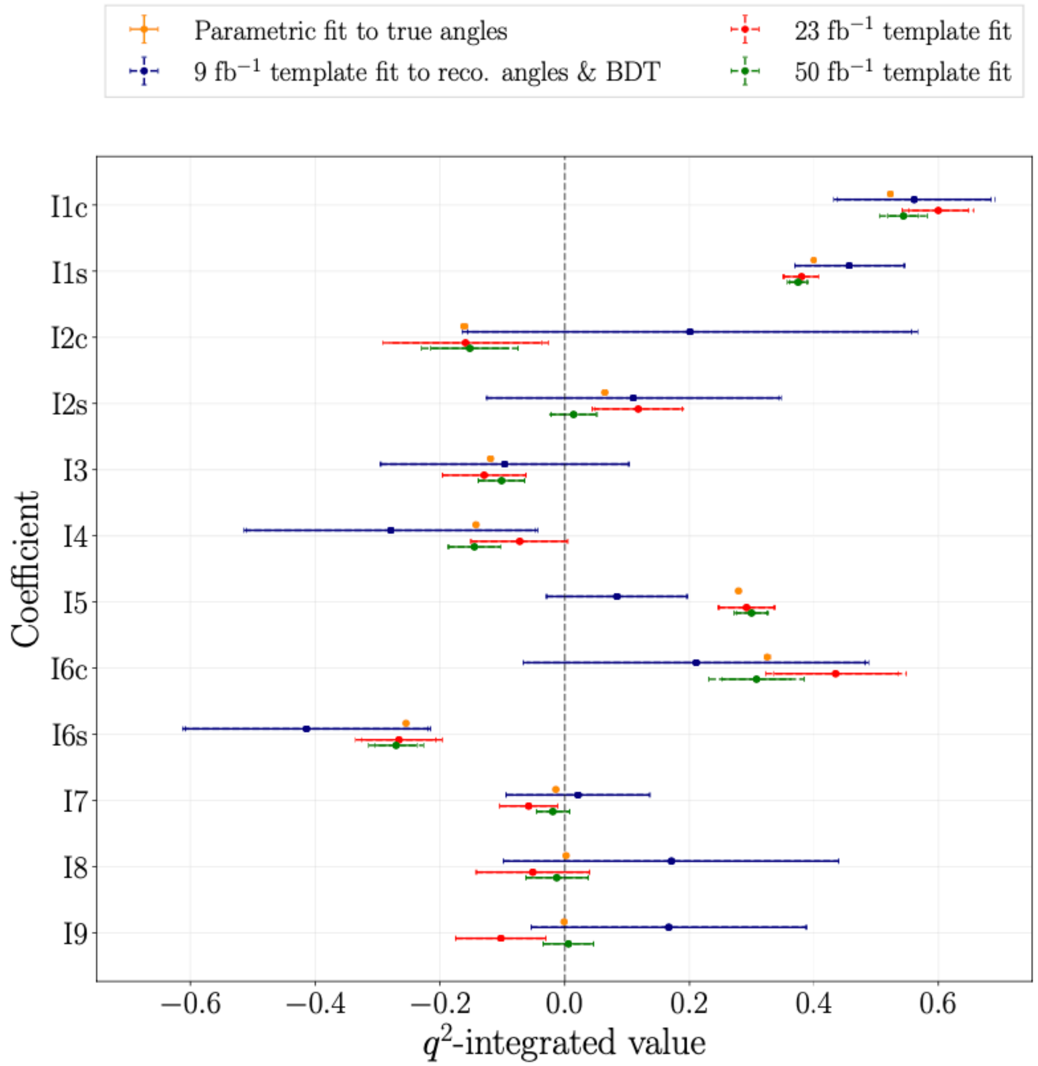


See: CERN-THESIS-2022-105

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

- LFV tests in $b \to cl\nu$ 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 $B \to D^* l\nu$ are ongoing
- Still lots more data to analyse from Run 1 and 2, and have now started Run 3!

Backup

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