$b \to c l \bar{\nu}$ decays at LHCb

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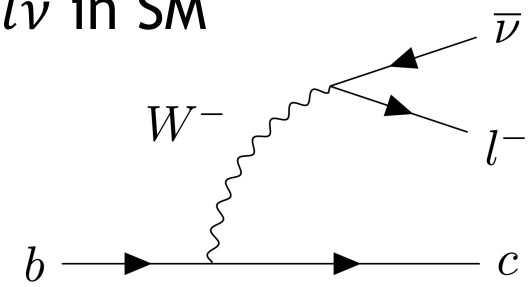
Moriond QCD 2024

2nd April, La Thuile, Italy

Physics opportunities in $b \to cl\bar{\nu}$ decays

- $b \to cl\bar{\nu}$ in SM

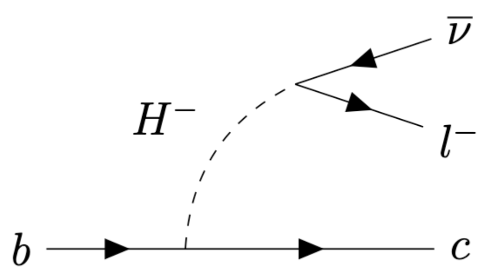


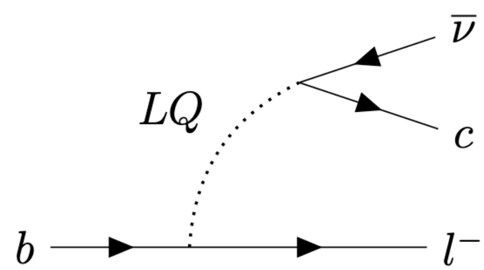
- CKM parameter $|V_{cb}|$
- b- and c-hadron properties

- **Search for New Physics (NP) beyond SM**

Charged Higgs

[PRL 116, 081801, ...]





Leptoquark

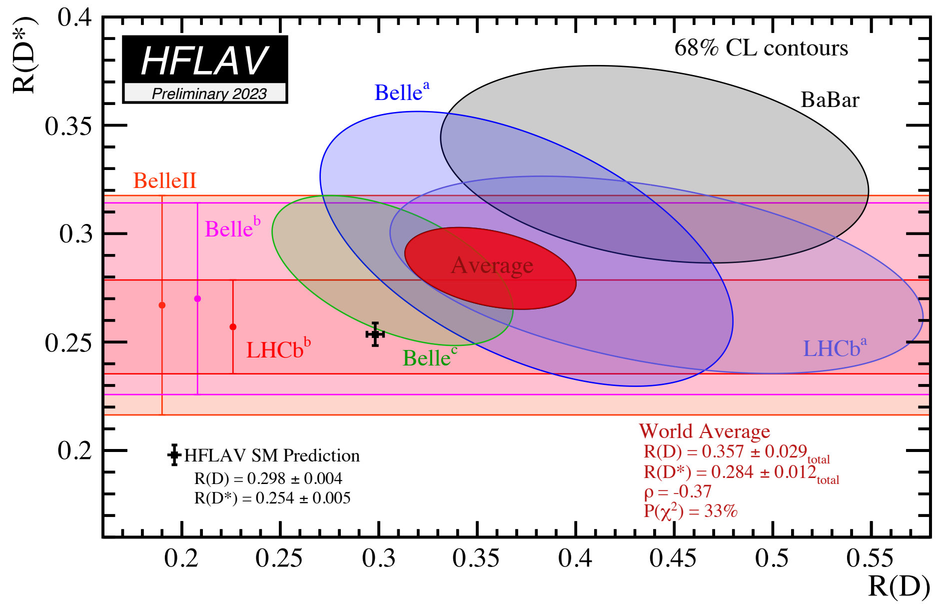
[PRL 116, 081801, PRD 94, 115021, ...]

- Violate Lepton Flavour Universality (LFU)
- Distort differential width shape from SM

LFU ratios

[HFLAV]

- $\mathcal{R}(H_c) = \frac{\mathcal{B}(H_b \to H_c \tau^+ \nu_\tau)}{\mathcal{B}(H_b \to H_c l^+ \nu_l)}$
  - $l \in \{e, \mu\}$; $H_{b(c)}$: $b(c)$-hadrons



$R(D)$&$R(D^*)$ anomaly from SM at 3.34σ

- More measurements are strongly motivated
  - To further improve $R(D)$&$R(D^*)$ precision
  - To extend physics programs
    - $R(H_c)$
    - Angular coefficients in $b \to c l \bar{\nu}$ decays

LFU tests in $b \to cl\bar{\nu}$ at LHCb

Muonic τ decay

- $R(D^{*+})$ Run1 (2015)
  - [PRL 115, 111803]
- $R(D^0)$&$R(D^*)$ Run1 (2023)
  - [PRL 131, 111802]
- **$R(D^+)$ & $R(D^{*+})$ part. Run2 (2024)**
  - [LHCb-PAPER-2024-007, in preparation]

New!

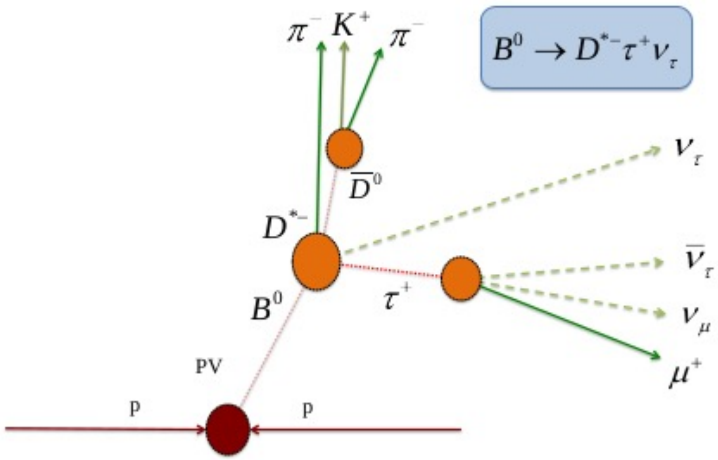
- $R(J/\psi)$ Run1 (2018)
  - [PRL 120, 121801]

Hadronic τ decay

- $R(D^{*+})$ Run1 (2018)
  - [PRL 120, 171802]
- $R(D^{*+})$ part. Run2 (2023)
  - [PRD 108, 012018]
- $R(\Lambda_c^+)$ Run1 (2022)
  - [PRL 128, 191803]
- **D^{*+} F_L Run1 & part. Run2 (2023)**
  - [arXiv:2311.05224]

τ-reconstruction strategies

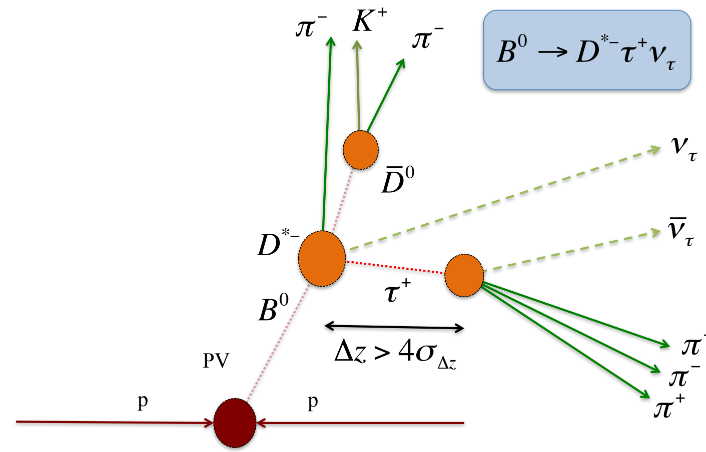
Muonic τ decay



- High statistics
- Directly measuring $R(D^*)$

- Multiple missing neutrinos
- Large backgrounds need to be controlled precisely

Hadronic τ decay



- High purity sample
  - Reconstructible τ decay vertex and specific $\tau \to 3\pi^{\pm}(\pi^0)$ dynamics
- Low statistics
- $R(D^*)$ needs external inputs

The two strategies are complementary and provide independent measurements

New!

$R(D^{+})$ & $R(D^{*+})$

[LHCb-PAPER-2024-007, in preparation]

$R(D^{+})$ & $R(D^{*+})$ strategy

LHCb 2015+2016 data $2\ \mathrm{fb}^{-1}$

- First LHCb measurement using D^{+} meson
  - $\tau \to \mu \bar{\nu}_{\mu} \nu_{\tau}$
  - $D^{*+} \to D^{+}\pi^{0}/\gamma$
  - $D^{+} \to K^{-}\pi^{+}\pi^{+}$
  - Visible final states: $D^{+}\mu^{-}$

$$R(D^{(*)+}) = \frac{\mathcal{B}(\bar{B}^{0} \to D^{(*)+}\tau^{-}\nu_{\tau})}{\mathcal{B}(\bar{B}^{0} \to D^{(*)+}\mu^{-}\nu_{\mu})} : \frac{\text{signal}}{\text{norm}}$$

Signal/norm efficiency ratio determined from simulation

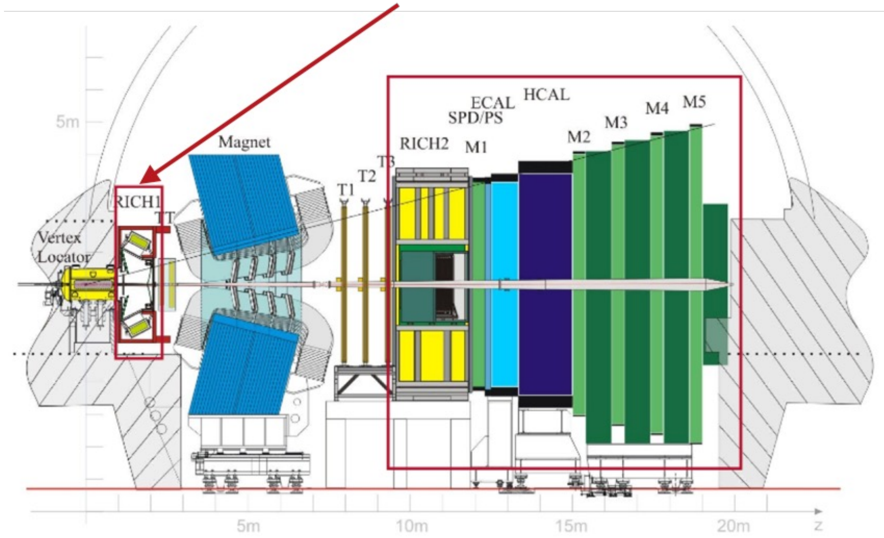
$$R(D^{(*)+}) = \frac{\epsilon_{\mu}^{D^{(*)+}}}{\epsilon_{\tau}^{D^{(*)+}}} \frac{N_{\tau}^{D^{(*)+}}}{N_{\mu}^{D^{(*)+}}} \frac{1}{\mathcal{B}(\tau^{-} \to \mu^{-}\nu_{\tau})}$$

Signal/norm yield ratio determined from fit to data

Simulation

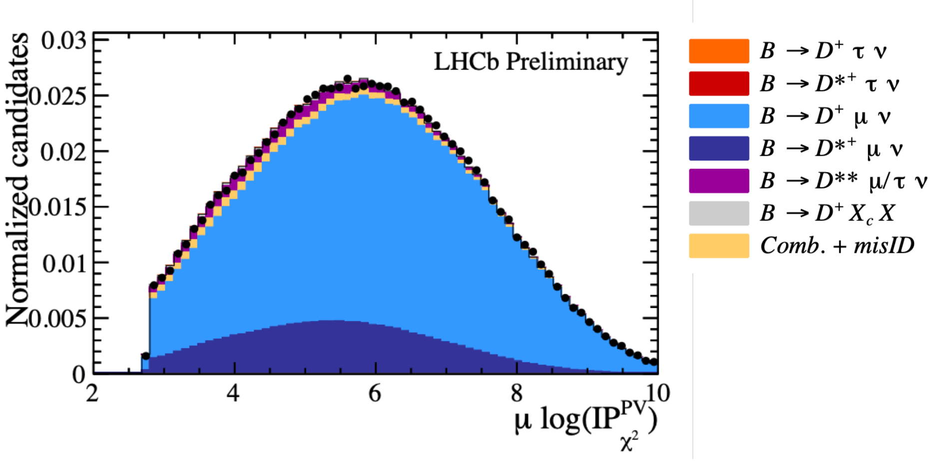
- To extract efficiency and fit model
- First analysis using Tracker-Only simulation
  - Missing detector effects emulated offline
  - ×8 faster than full simulation
  - Enable producing large amount of simulation samples to reduce the related systematic uncertainty

Sub-detector response turned off



- Data/simulation corrections
  - B kinematic, multiplicity, …
  - QED effects [PRL 120, 261804 (2018)]

Excellent agreement obtained!

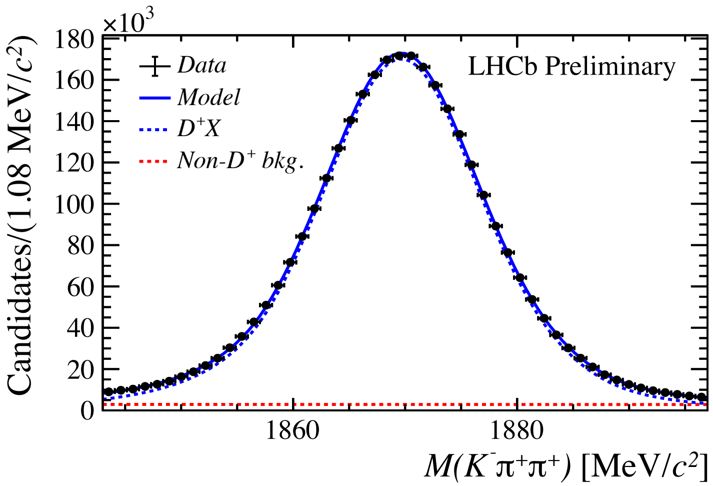


(Norm decay enhanced sample)

Background reduction

- Selection
  - Topologic, kinematic and PID requirements on $K^-\pi^+\pi^+\mu^-$ candidates
  - Isolation against partially reconstructed backgrounds with missing charged and neutral final states

- Subtraction of combinatorial D^+ background
  - Fit to $M(K^-\pi^+\pi^+)$ and extract signal D^+ using sPlot method



Strategy to extract signal & norm yields

- 3D binned template fit to data
  - $q^2 = (p_{\bar{B}^0} - p_{D^+})^2$
  - E_l^* : μ energy in $\bar{B}^0$ rest frame
  - m_{miss}^2: invariant-mass of unreconstructed particles

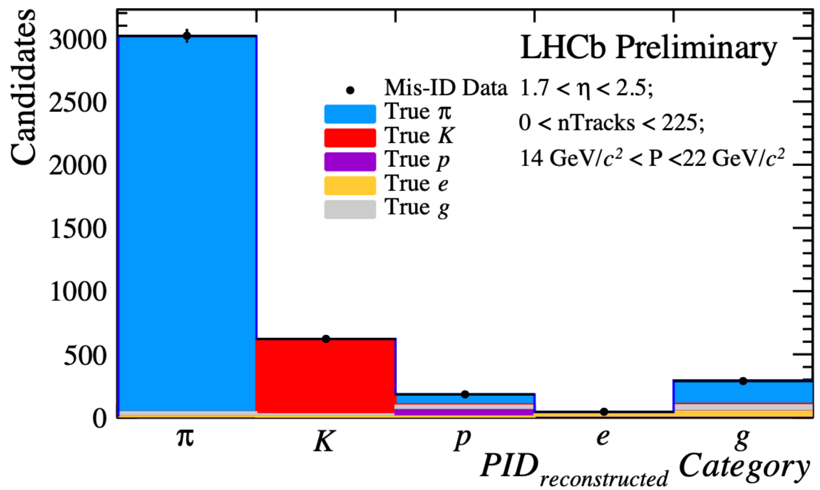
- Simultaneous fit to four data samples with different kinds of decays enhanced in each sample
  - Signal sample: $D^+\mu^-$
  - 3 control samples to provide constraints to backgrounds
    - $D^+\mu^-\pi^-$ and $D^+\mu^-\pi^+\pi^-$: $B \to D^{**}l^-\nu_l$
    - $D^+\mu^-K^+$: $B \to D^+H_cX,\ H_c \to X'l^-\nu_l$

$l \in \{\mu, \tau\}$

Template construction

- Simulation-based templates
  - Signal and norm decays
  - Feed down from D^{**}
  - Double charm background
  - $\Lambda_b^0 \to nD^+\mu^-\bar{\nu}_\mu$ background
- Data-based templates
  - μ mis-ID background: D^+h^-
    - Obtained from μ-suppressed data sample
    - Contamination fractions of different particle species unfolded
  - Combinatorial background:
    - Wrong-sign $D^+\mu^+$ data sample

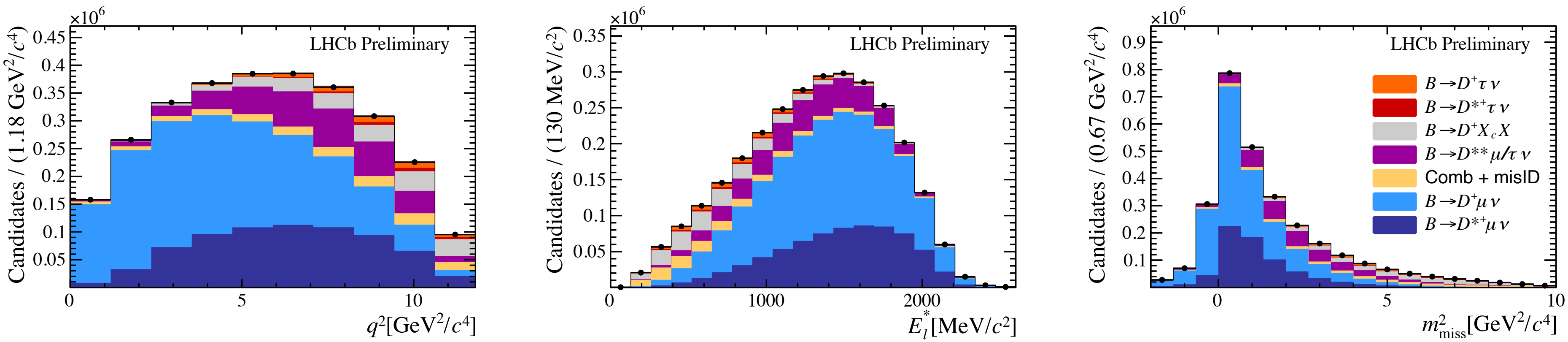
- Form factors
  - $B \to D^{(*)+}$: BGL [PRD 94 (2016) 094008, Eur. Phys. J. C 82, 1141 (2022)]]
  - $B \to D^{**}$: BLR [PRD 95 (2017) 014022]
- Form factor parameters varied in the template fit with external constraints
  - First analysis uses HAMMER [Eur. Phys. J. C. 80 (2020) 883] to do so
    - Implemented in RooHammerModel class [JINST 17 (2022) T04006]



g: host (fake) tracks

Results

- Fit projections in the signal sample



$$R(D^+) = 0.249 \pm 0.043(\text{stat}) \pm 0.047(\text{syst})$$
$$R(D^*) = 0.402 \pm 0.081(\text{stat}) \pm 0.085(\text{syst})$$

$$\rho = -0.39$$

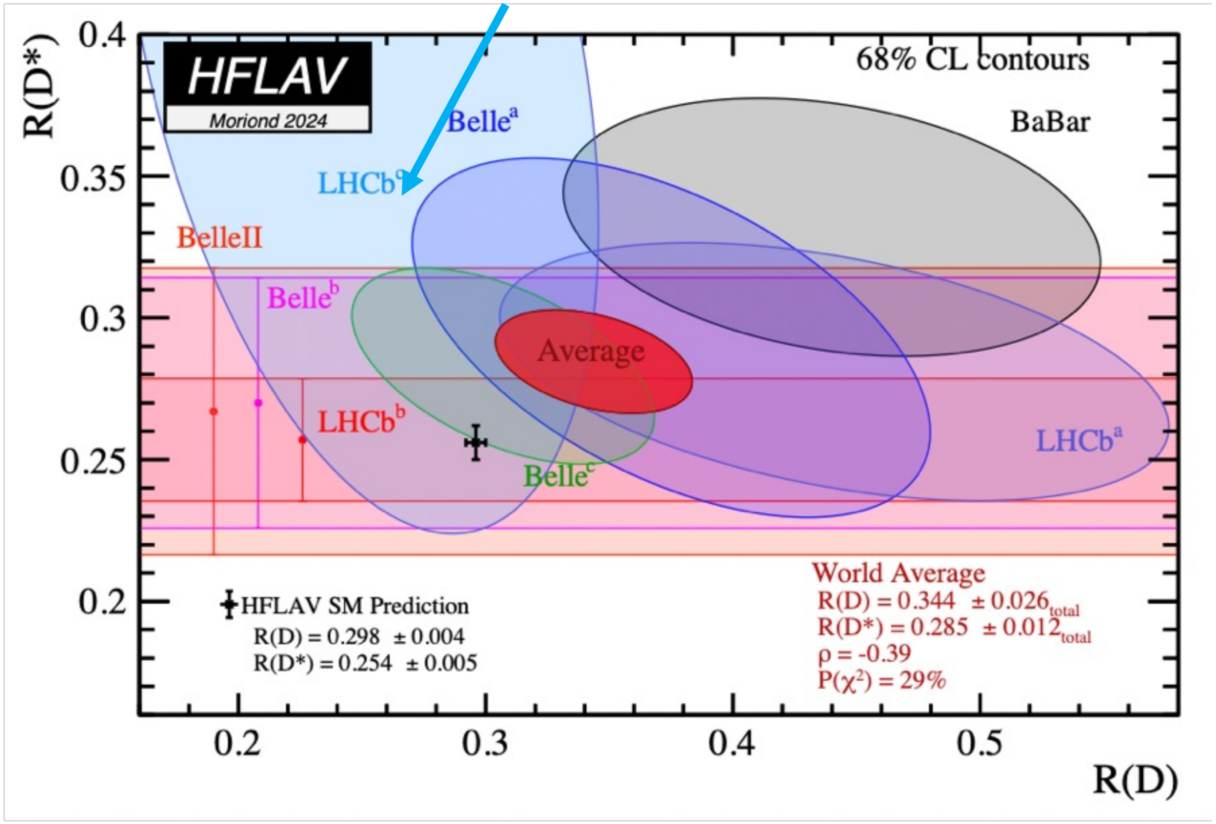
Source	$\mathcal{R}(D^+)$	$\mathcal{R}(D^{*+})$
Form factors	0.023	0.035
$B \to D^{**}[D^+X]\mu/\tau\nu$ fractions	0.024	0.025
$B \to D^+X_cX$ fractions	0.020	0.034
Misidentification	0.019	0.012
Simulation size	0.009	0.030
Combinatorial background	0.005	0.020
Data/simulation agreement	0.016	0.011
Muon identification	0.008	0.027
Multiple candidates	0.007	0.017
Total systematic uncertainty	0.047	0.086

- Main systematic uncertainties:
  - Form factor parameterisation
  - Background modelling

New $R(D)$ & $R(D^*)$ world average

This result

HFLAV



Tension with SM: $3.34\sigma \rightarrow 3.17\sigma$

D^* longitudinal polarisation in $B^0 \to D^{*-}\tau^+\nu_\tau$

[arXiv:2311.05224]

arXiv:2311.05224

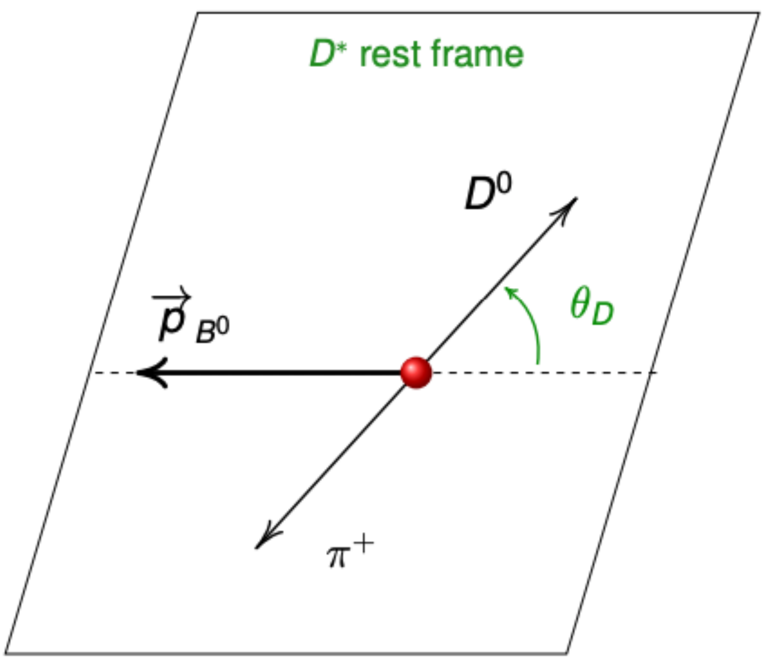
D^* polarisation

Polarised fraction

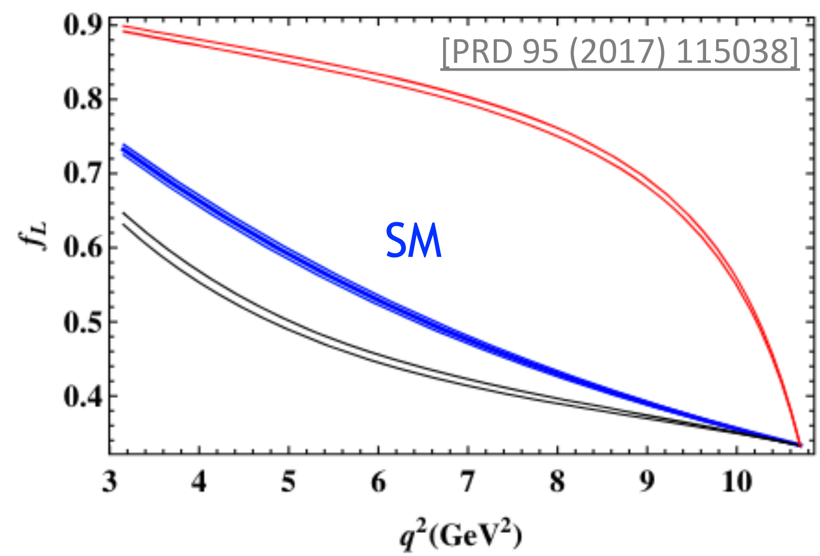
$$\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$$

Unpolarised fraction

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



- New Physics can affect $F_L^{D^*}(q^2)$ shape:
  - Black & red: two New Physics configurations

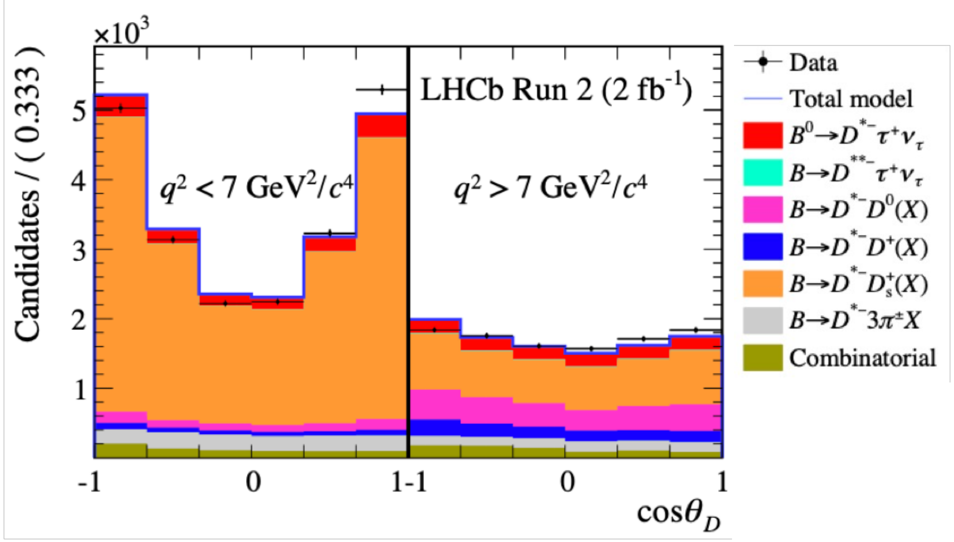


arXiv:2311.05224

D^* polarisation measurement

- Data: Run1, 2015+2016 $B^0 \to D^{*-}\tau^+\nu_\tau$, $\tau^+ \to 3\pi^{\pm}(\pi^0)\bar{\nu}_\tau$
- Background suppression and control similar to Run 2 $R(D^*)$ analysis
  - [PRD 108, 012018]
- $F_L^{D^*}$ determined using 4D binned template fit
  - τ^+ lifetime, $\cos\theta_D$, anti-Ds BDT, q^2

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

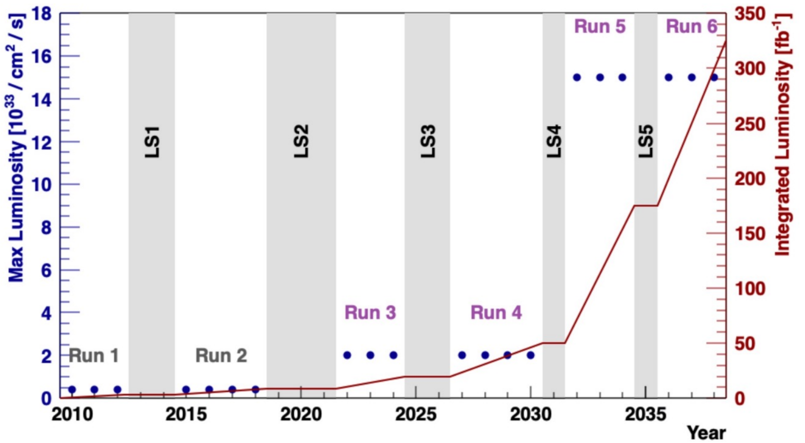


- Main systematic uncertainties:
  - Size of simulation sample
  - Form factor parameterisation
    - Vary CLN parameters
    - CLN -> BGL
  - Double charm background description

- Results compatible with Belle result and SM:
  - [arXiv:1903.03102, Phys.Rev.D 98 (2018) 9, 095018, Eur.Phys.J.C 79 (2019) 3, 268, arXiv:1907.02257, arXiv:2310.03680]

Summary and prospects

- **New LHCb result in test of LFU**
  - $R(D^+)\&R(D^{*+})$ with muonic τ decay: compatible with world average and SM
  - New world average still at 3σ level away from SM
- **First LHCb measurement of D^{*-} longitudinal polarisation**
  - First measured in two q^2 bins
  - Most precise result
  - Compatible with previous result and SM prediction
- **More are coming**
  - Update $R(D)\&R(D^*)$ in more channels and using more data
  - LFU tests for other charm/light hadrons
  - Angular observables to probe spin structure of New Physics
  - …



Thanks for your attention!

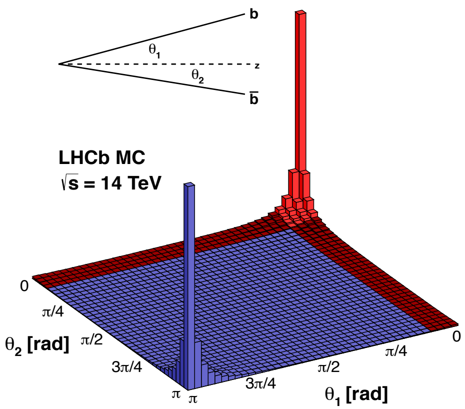
Backup slides

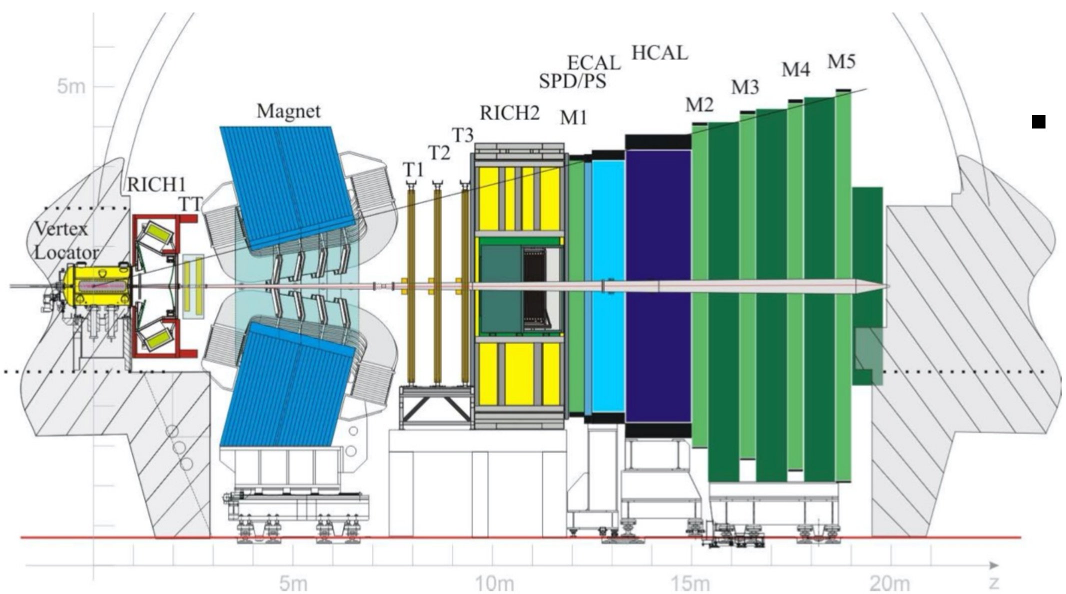
LHCb experiment

JINST 3 (2008) S08005, Int.J.Mod.Phys. A30 (2015) 1530022

- Dedicated for precise and efficient heavy-hadron reconstruction
  - Single-arm and forward design

$2 < \eta < 5$ range: ~25% $b\bar{b}$ pairs in LHCb acceptance

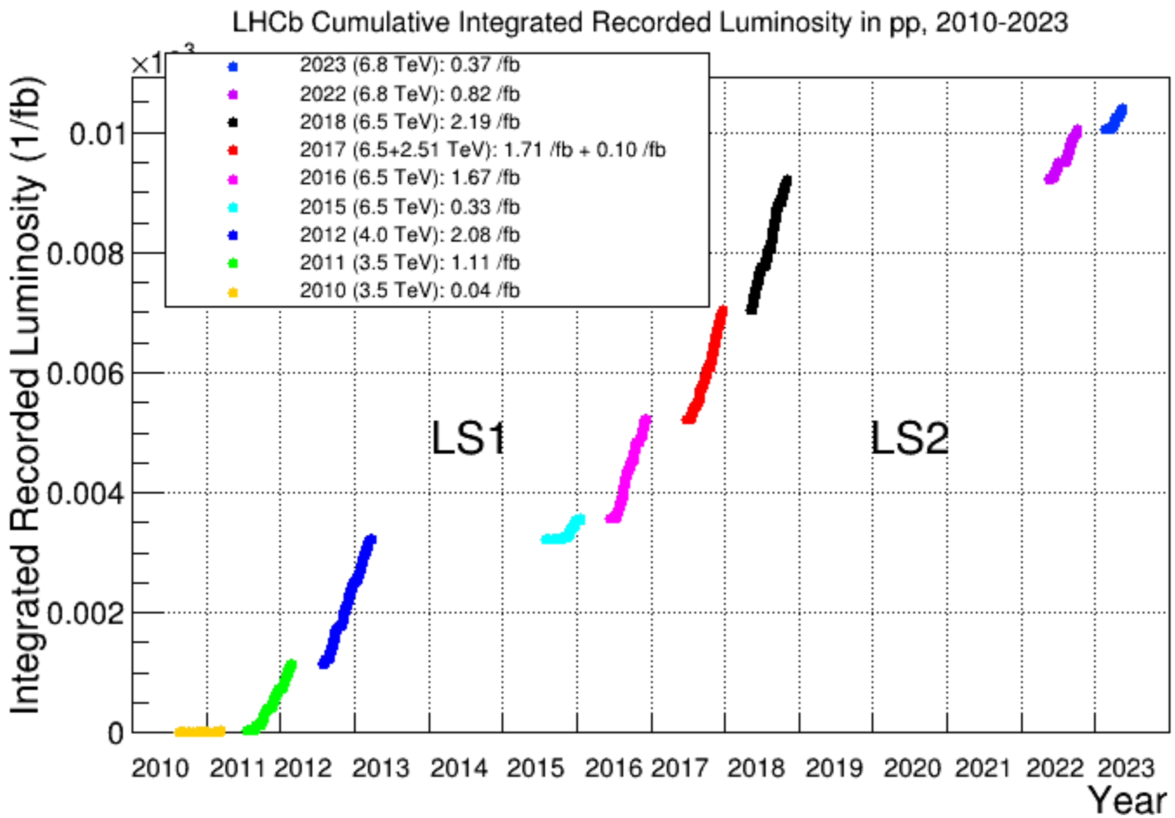




- Powerful particle identification
  - $\epsilon(K \to K) \sim 95\%$ with $\epsilon(\pi \to K) \sim 5\%$
  - $\epsilon(\mu \to \mu) \sim 97\%$ with $\epsilon(\pi \to \mu) \sim 1-3\%$
- High momentum resolution
  - $\Delta p/p = 0.4 \sim 0.6\%$ $(5-100\mathrm{GeV}/c)$
- High spatial resolution
  - σ_{IP}~20μm; $\sigma_{\mathrm{PV},x/y}$~10μm; $\sigma_{\mathrm{PV},z}$~60μm
  - Precise PV and decay vertex reconstructions

LHCb pp dataset

- Run1: 3 fb^{-1} pp collision @ 7, 8 TeV
- Run2: 6 fb^{-1} pp collision @ 13 TeV
- Run3: started in 2022



Neutrino reconstruction

- For muonic decay:
  - $p_{B_z} = \frac{m_B}{m_Y} p_{Y_z}$
  - p_B direction aligns with the vector connecting B decay vertex and associated PV

- For hadronic τ decay:
  - Four-momentum conservation
  - Constraints of τ and B known masses
  - p_B direction aligns with the vector connecting B vertex and associated PV
  - p_τ direction aligns with the vector connecting τ and B vertices
  - Solve equations to determine missing momentum with two-fold ambiguity

Enhanced components in the four samples

- Simultaneous fit to four data samples with different kinds of decays enhanced in each sample

Sample	Component		
Signal sample $D^+\mu^-$	Signal & norm:	$\bar{B}^0 \to D^+\tau^-[\mu^-\nu_\tau\bar{\nu}_\mu]\bar{\nu}_\tau$ $\bar{B}^0 \to D^{*+}[D^+\pi^0/\gamma]\tau^-[\mu^-\nu_\tau\bar{\nu}_\mu]\bar{\nu}_\tau$	$\bar{B}^0 \to D^+\mu^-\bar{\nu}_\mu$ $\bar{B}^0 \to D^{*+}[D^+\pi^0/\gamma]\mu^-\bar{\nu}_\mu$
1π sample $D^+\mu^-\pi^-$	1P D^{**}:	$B \to D^{**}[D^+X]\tau^-[\mu^-\nu_\tau\bar{\nu}_\mu]\bar{\nu}_\tau$	$B \to D^{**}[D^+X]\mu^-\bar{\nu}_\mu$
2π sample $D^+\mu^-\pi^+\pi^-$	Higher D^{**}:	$B \to D^{**}[D^+X]\tau^-[\mu^-\nu_\tau\bar{\nu}_\mu]\bar{\nu}_\tau$	$B \to D^{**}[D^+X]\mu^-\bar{\nu}_\mu$
1K sample $D^+\mu^-K^\pm$	Double charm:	$B \to D^+H_c[\mu^-\bar{\nu}_\mu X]X'$	

PDF

$$PDF(q^2, m^2_{miss}, E_\ell) = 1/N_{tot} \times \{R_{raw}(D^+)N_{D^+\mu}\mathcal{P}_{D^+\tau} + N_{D^+\mu}\mathcal{P}_{D^+\mu} + \quad (19)$$

$$R_{raw}(D^{*+})N_{D^+\mu}\mathcal{P}_{D^{*+}\tau} + N_{D^{*+}\mu}\mathcal{P}_{D^{*+}\mu} + \quad (20)$$

$$N_{D_1^0\mu}\mathcal{P}_{D_1^0\mu} + f_{D_0^0}N_{D_1^0}\mathcal{P}_{D_0^0\mu} + \quad (21)$$

$$f_{D_1^{0\prime}}N_{D_1^0}\mathcal{P}_{D_1^{0\prime}\mu} + f_{D_2^0}N_{D_1^0}\mathcal{P}_{D_2\mu} + \quad (22)$$

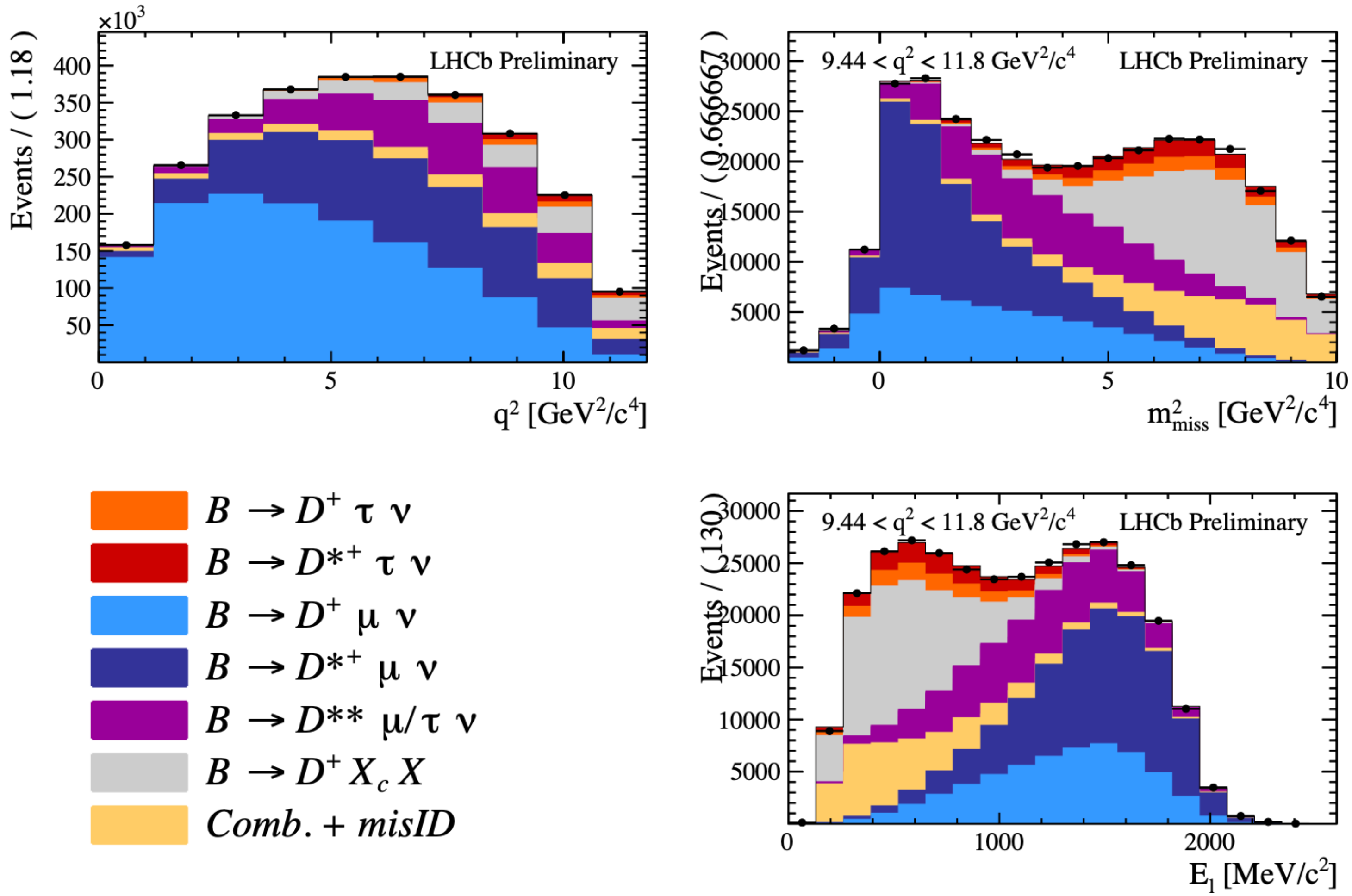
$$f_{D_0^+}N_{D_1^0}\mathcal{P}^+_{D_0\mu} + f_{D_1^{+\prime}}N_{D_1^+}\mathcal{P}_{D_1^{+\prime}\mu} + \quad (23)$$

$$f_{D_2^+}N_{D_1^0}\mathcal{P}^+_{D_2\mu} + R_{raw}(D^{**})N_{D^{**}}\mathcal{P}_{D^{**}\tau} + \quad (24)$$

$$N_{DD}\mathcal{P}^d_{DD} + f_{B_u}N_{DD}\mathcal{P}^u_{DD} + f^d_{D_s^+\to\tau}\mathcal{P}^d_{DD} + f^u_{D_s^+\to\tau}\mathcal{P}^u_{DD} + \quad (25)$$

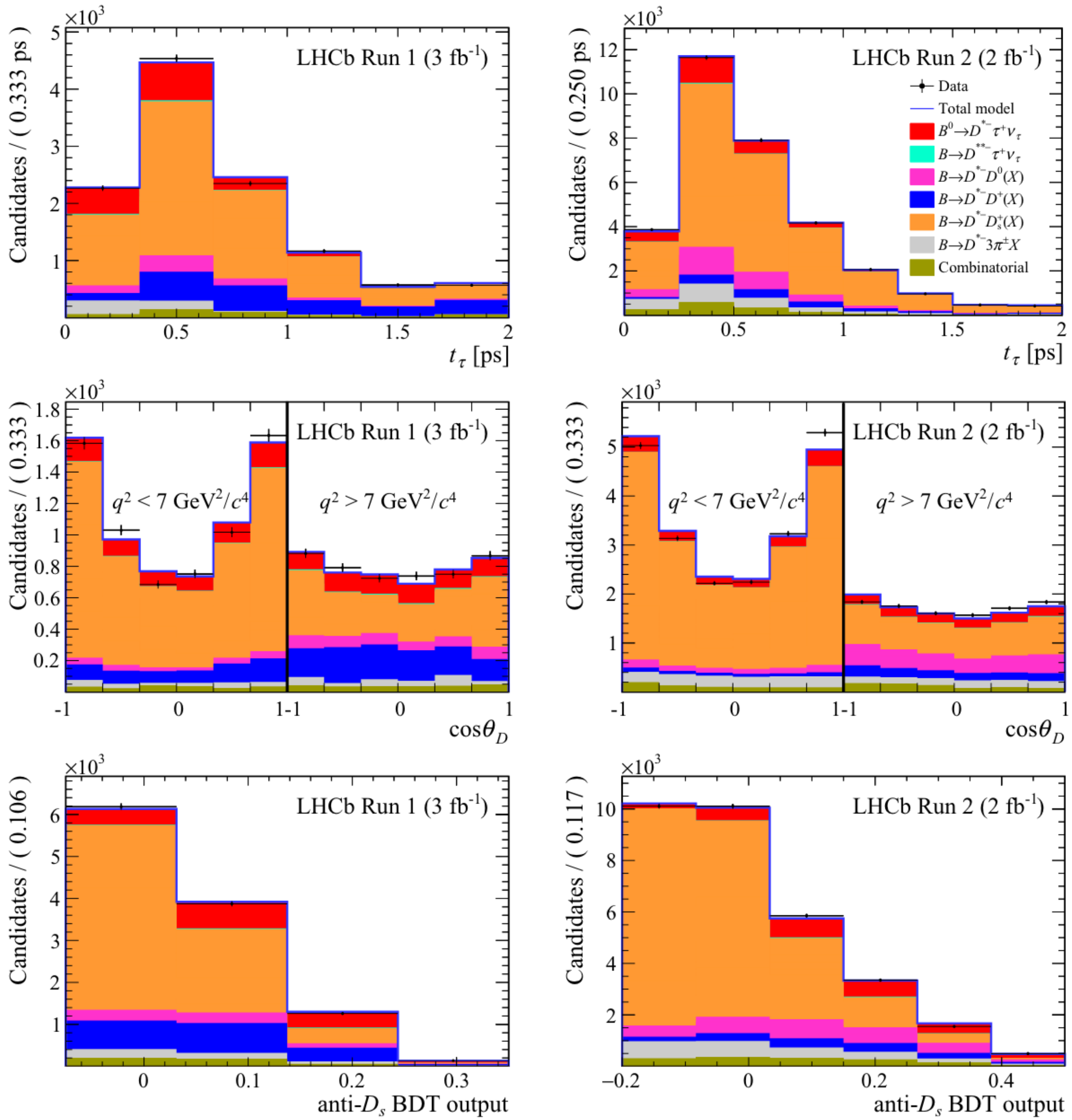
$$N^{3body}_{DD}\mathcal{P}^{3body}_{DD} + f^{3body}_{B_u}N^{3body}_{DD}\mathcal{P}^{3body}_{DD}\} \quad (26)$$

More plots in $R(D^+)$ & $R(D^{*+})$ analysis



arXiv:2311.05224

More plots in $F_L^{D^*}$ analysis



(Phys. Rev. D108 (2023) 012018)

$F_L^{D^*}$ systematic uncertainties

Source	low q^2	high q^2	integrated
Fit validation	0.003	0.002	0.003
FF model	0.007	0.003	0.005
FF parameters	0.013	0.006	0.011
TemplateSize	0.027	0.017	0.019
$\tau^+ \to 3\pi^\pm\pi^0$ fraction	0.001	0.001	0.001
D^{**} feed-down	0.001	0.004	0.003
Signal selection	0.005	0.004	0.005
Bin migration	0.008	0.006	0.007
$F_L^{D^*}$ in simulation	0.007	0.003	0.007
D_s decay model	0.008	0.009	0.009
$\cos\theta_D$ $D^{*-}D_s$	0.002	0.001	0.002
$\cos\theta_D$ $D^{*-}D_s^{*+}$	0.007	0.002	0.004
$\cos\theta_D$ $D^{*-}D_sX$	0.007	0.006	0.007
$\cos\theta_D$ $D^{*-}D^+X$	0.002	0.002	0.003
$\cos\theta_D$ $D^{*-}D^0X$	0.002	0.002	0.003
$F_L^{D^*}$ integrated	-	-	0.002
Total	0.036	0.023	0.029

Dominant source of systematic are:

- Limited size of the simulation samples
- Form factor parameterization
- Modelling of the D_s
- $\cos\theta_D$ shape in $D^{*-}D_sX$ backgrounds
- Bin migration
- Signal acceptance
- Form factor model