LFU tests in semileptonic decays at LHCb

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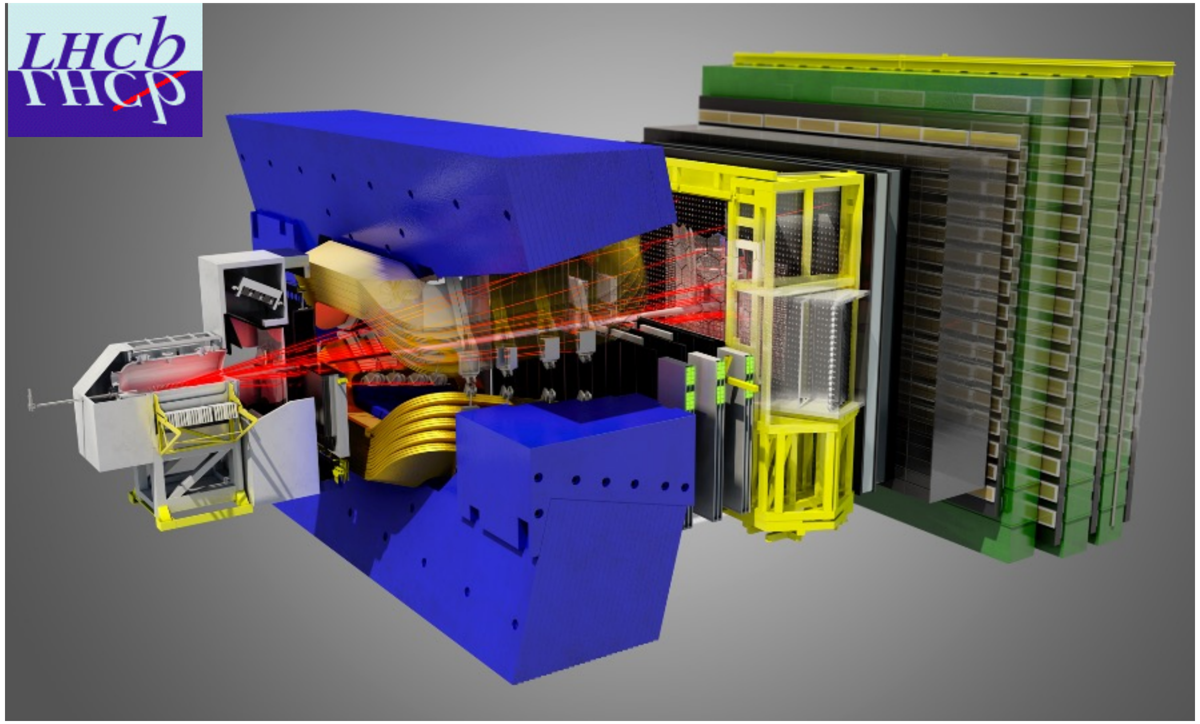
On behalf of the LHCb Collaboration

OUTLINE

- Ratios of branching ratio
  - $R(D^0)$, $R(D^*)$ with muonic and hadronic tau decays
  - Other $R(X_c)$ measurements
- Angular analysis
  - $F_L^{D^*}$ in $B \to D^* \tau \nu$
- I will **not** report on
  - LFU in rare decays FCNC transitions → M. Borsato's talk
  - Prospects on semileptonic decays → M. Rotondo's talk



Data collected at LHCb in

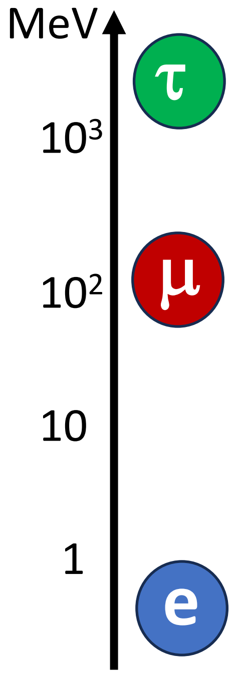
- Run 1 at $\sqrt{s}$=7,8 TeV, 3 fb^{-1}
- Run 2 at $\sqrt{s}$=13 TeV, 6 fb^{-1} (but only 2 fb^{-1} used for today results)

LEPTON FLAVOUR UNIVERSALITY

In the Standard Model (SM):

- Three families of leptons, with a mass scaling factor ~10^4
  - we don't know the origin and the reason for this multiplicity and mass differences
- LFU= the electroweak couplings to all charged leptons are universal, differences between e, μ, and τ are driven only by masses
  - no known symmetry principle behind this

→ deviations from LFU can provide multiple suggestions for building NP models

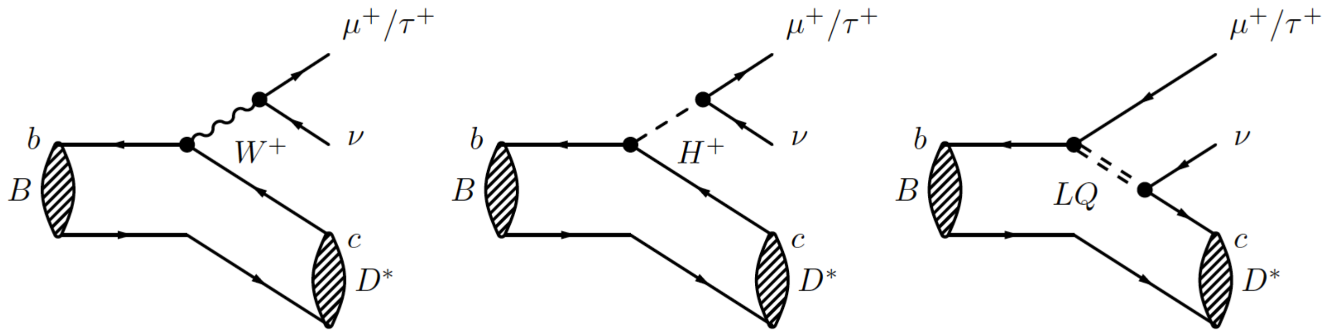


- Symmetry between e and μ well tested by several experiments, τ-sector less explored
  - New Physics with heavy mediator can prefer τ coupling

R(D$^{(*)}$) MEASUREMENTS IN SEMILEPTONIC B DECAYS

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)} \qquad \ell = e, \mu$$

- Powerful tests of LFU from ratios of branching fractions of B decays involving different leptons
  - Charged Current b→ c l ν transitions, dominated by tree level diagrams.
  - Hadronic uncertainties (form factors) mostly cancel in the ratio →precise theory predictions possible
  - Reduced experimental systematic uncertainties in ratios of efficiencies
- Sensitive to presence of NP, e.g charged Higgs, leptoquarks

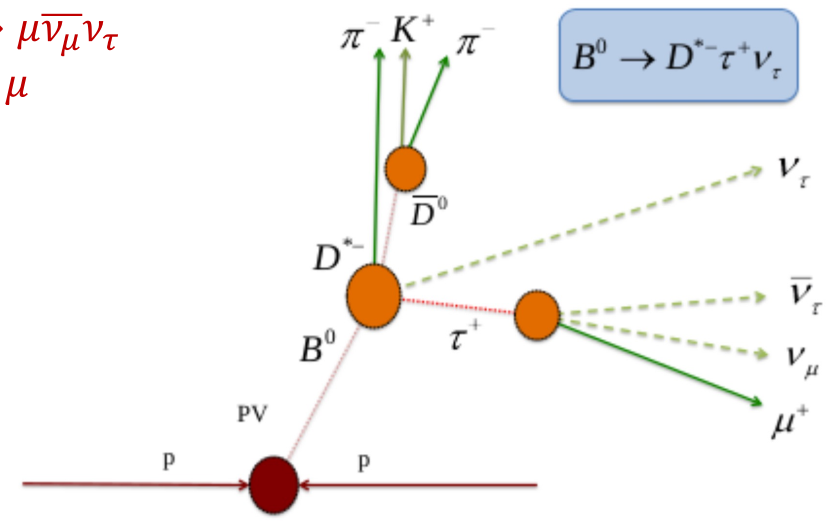


R(D$^{(*)}$) MEASUREMENTS at LHCb

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

Muonic tau decay

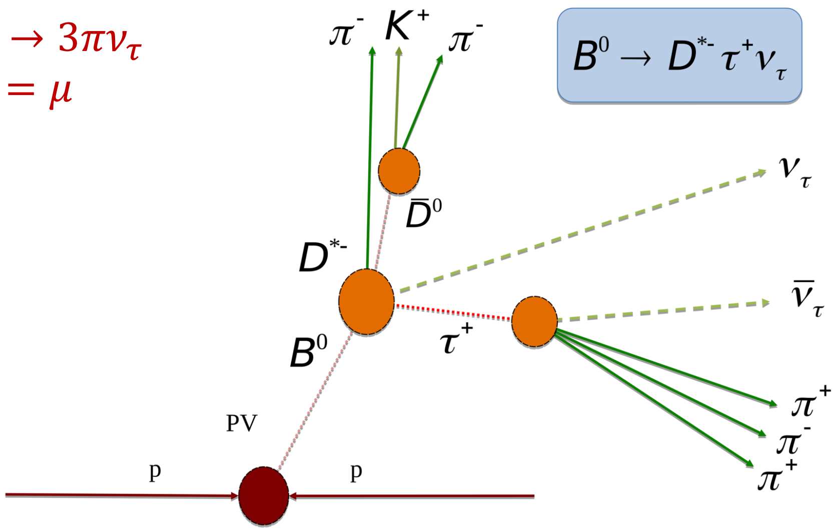
$\tau \to \mu\overline{\nu_\mu}\nu_\tau$
$\ell = \mu$



- Same final state for signal and normalization mode: direct measurement of R(D$^{(*)}$)
- High tauonic branching ratio
- Three neutrinos in final state: no mass peak, high background from partially reconstructed decays (DD, D**...)

Hadronic tau decay

$\tau \to 3\pi\nu_\tau$
$\ell = \mu$



- Three pions vertex provides tau decay position: suppress dominant background
- Exploit the specific dynamics of $\tau \to 3\pi\nu$ decay
- Lower BR but higher purity sample
- Measurement of R(D*) requires external inputs

$R(D^0)$-$R(D^*)$ WITH MUONIC TAU DECAYS at LHCb

Phys. Rev. Lett. 131, 111802

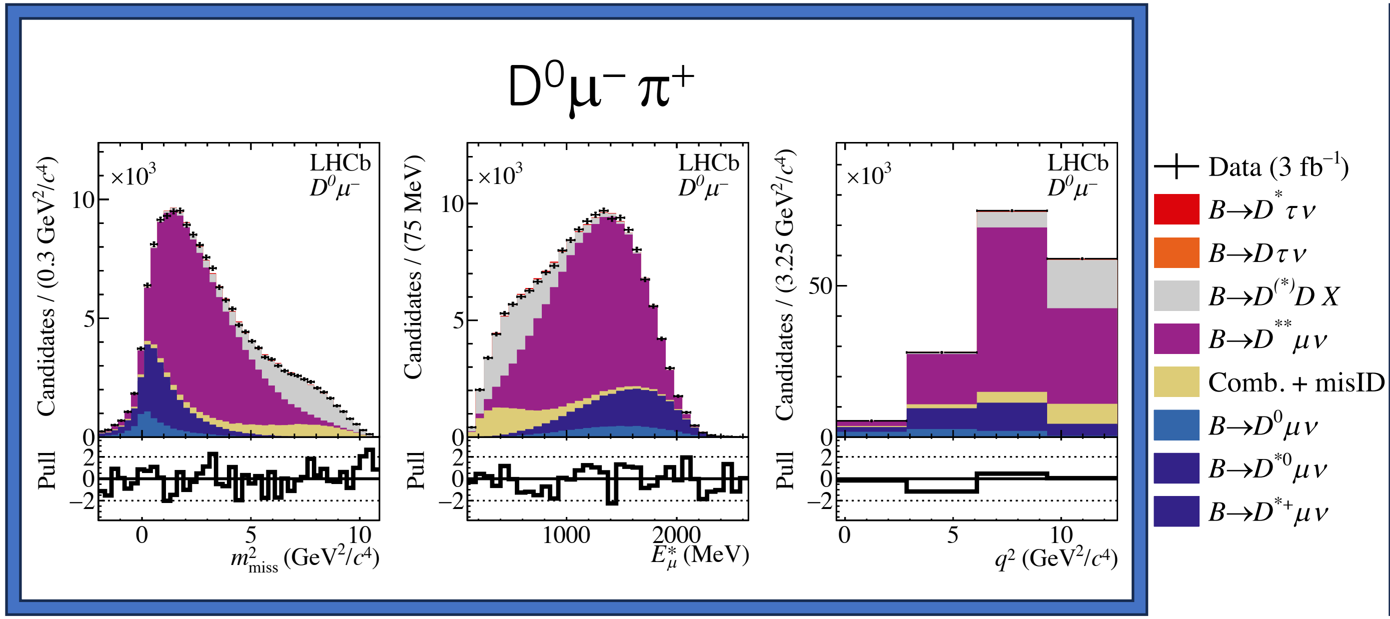
- Simultaneous measurement of $R(D^0)$ and $R(D^*)$ with $D^0\mu^-$ and $D^{*+}\mu^-$ samples
  - Run1 data (supersedes Phys. Rev. Lett. 115, 111803)
  - Higher branching fraction and higher efficiency for the $D^0\mu^-$ sample
    - Veto $D^{*+} \rightarrow D^0\pi^+$ in the $D^0\mu^-$ sample (exclusive samples)
- No direct knowledge on B momentum, rest frame kinematics determined as
  - p_T of missing momentum from B flight direction
  - p_L from boost approximation: $\gamma\,\beta_{z,total} = \gamma\,\beta_{z,visible}$

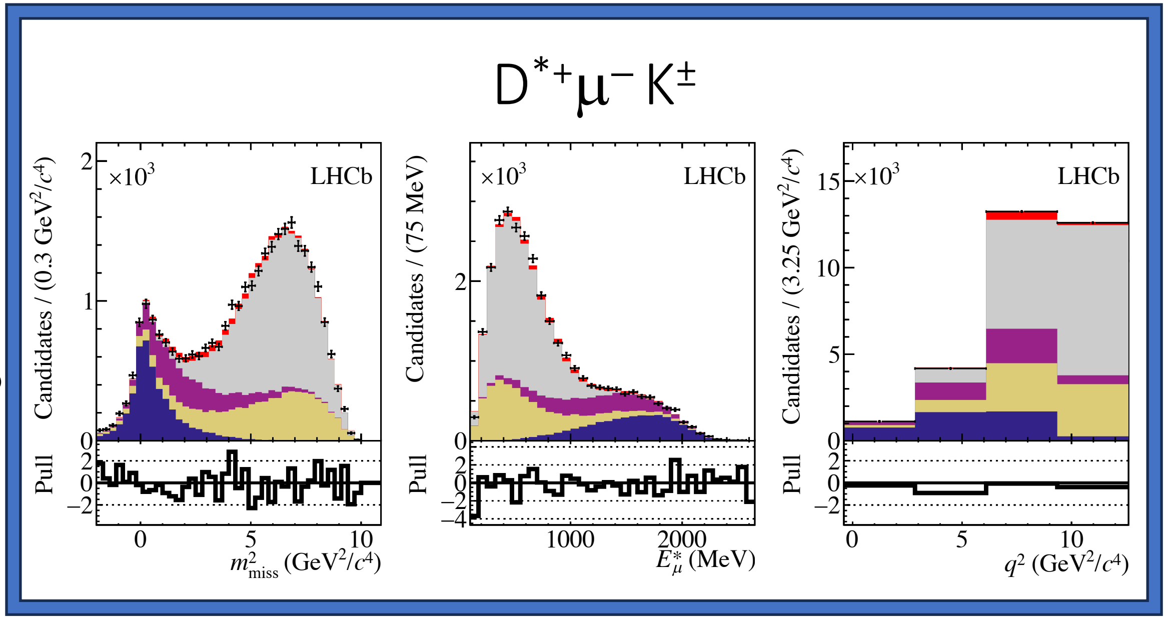
  → ~20% resolution on B momentum
- Use rest-frame quantities to distinguish signal in 3D fits: $m^2_{missing}$, E_μ , $q^2 = (p_B-p_D)^2$

R(D^0) AND R(D*) MUONIC - BACKGROUND

Phys. Rev. Lett. 131, 111802

- Physics backgrounds with additional charged tracks rejected with isolation discriminant
  - Inverting the cut provides control samples enriched in background ($D^{(*)}\mu$ + 1π,2π,1K). Used to constrain background modelling.
  - Background from misidentified muons and combinatorial also from data samples.
- Maximum likelihood fit to isolated signal regions and anti-isolated control regions





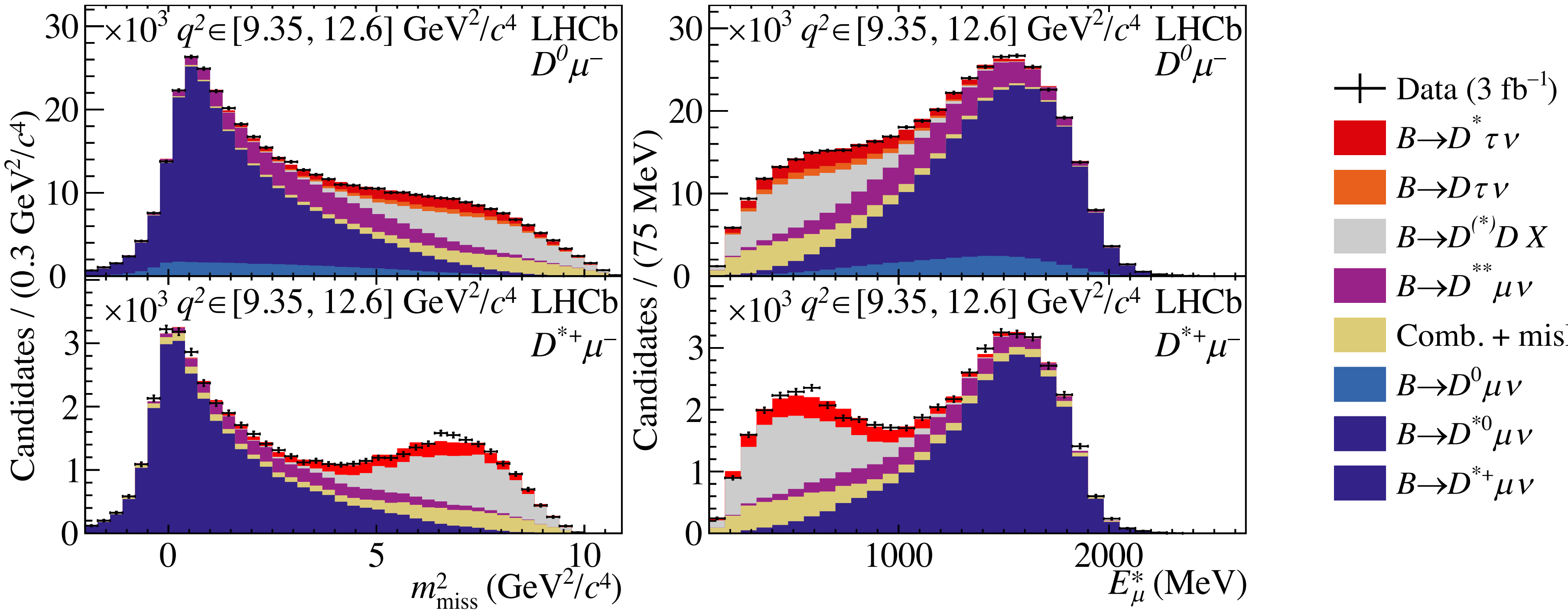
R(D^0) AND R(D*) - RESULT

Phys. Rev. Lett. 131, 111802

isolated signal region at high q^2

$D^0\mu^-$

$D^{*+}\mu^-$



R(D*) = 0.281 ± 0.018(stat) ± 0.024(syst)

R(D^0) = 0.441 ± 0.060(stat) ± 0.066(syst) ρ= – 0.43

- In agreement with R(D*)-R(D) world-average, 1.9 σ above the SM prediction.
- Main systematic uncertainties: limited size of simulated sample and effect of shape parameters derived from control regions.

$R(D^*)$ WITH HADRONIC TAU DECAYS

Phys. Rev. D 108, 012018

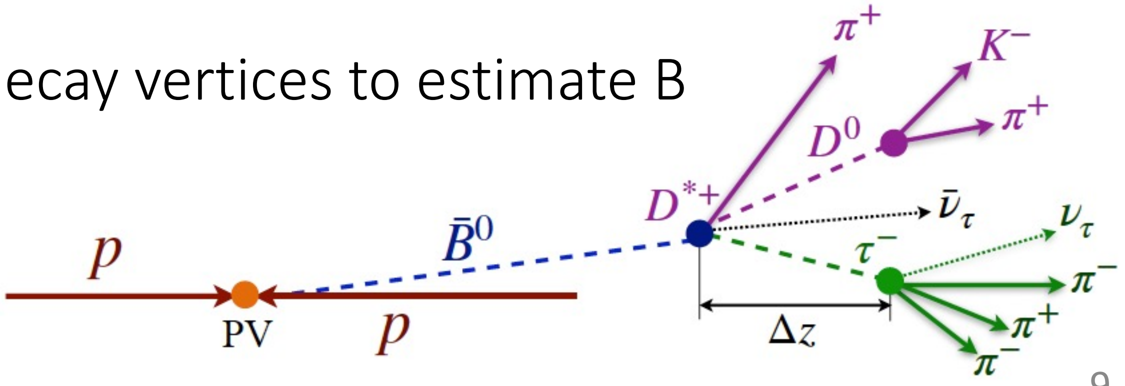
- $R(D^*)$ with $\tau^+ \rightarrow \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$, $D^{*-} \rightarrow \bar{D}^0\pi^-$ (2fb^{-1} 2015+16 Run2 data)
- Measure the ratio

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}$$

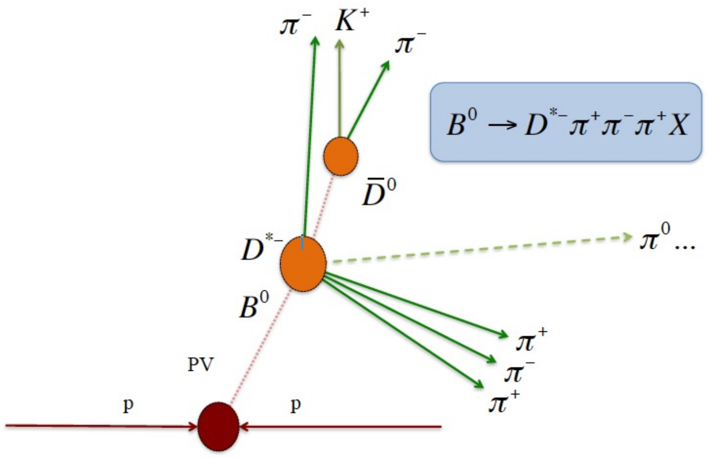
- Use external inputs to derive

$$R(D^*) = \mathcal{K}(D^*) \left\{ \frac{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)} \right\}_{\text{ext. input}}$$

- Use precise knowledge of the D^0, 3π and B^0 decay vertices to estimate B momentum



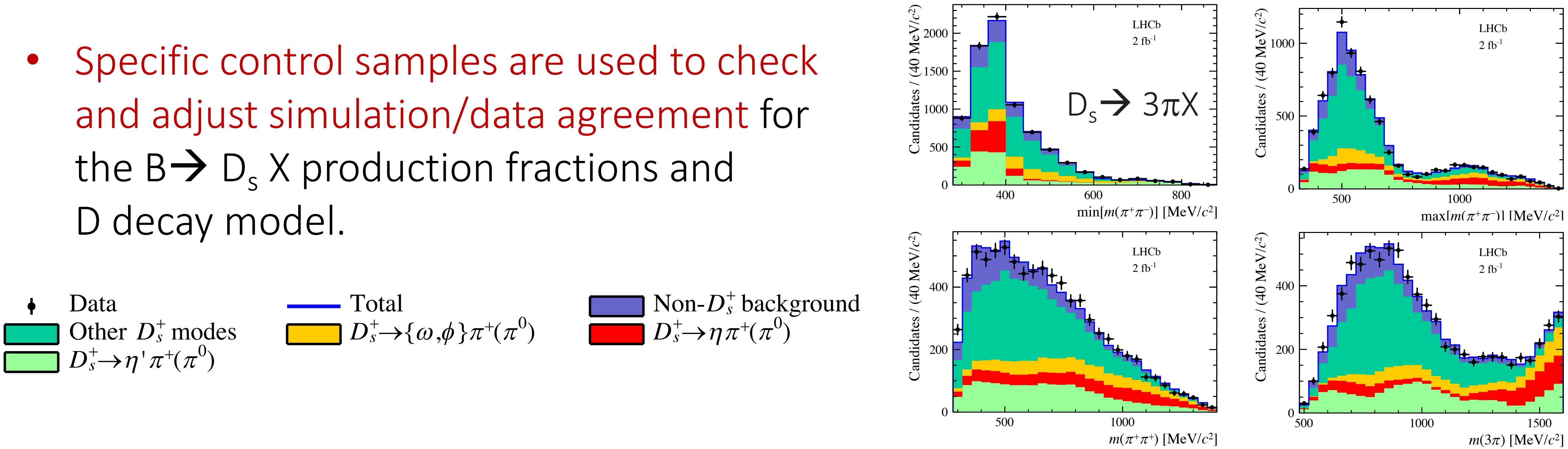
R(D*) HADRONIC - BACKGROUND



- Dominant background (100x) B→D*3π± X rejected with detached tau vertex cut (>99%)
  - Exclusive B→D*3π± decays selected as normalization mode

- Double charm decays B→ D*DX with D=D_s / D^+/D^0 -> 3π± X'
  - BDT trained to reject dominant D_s component (also used as fit variable).

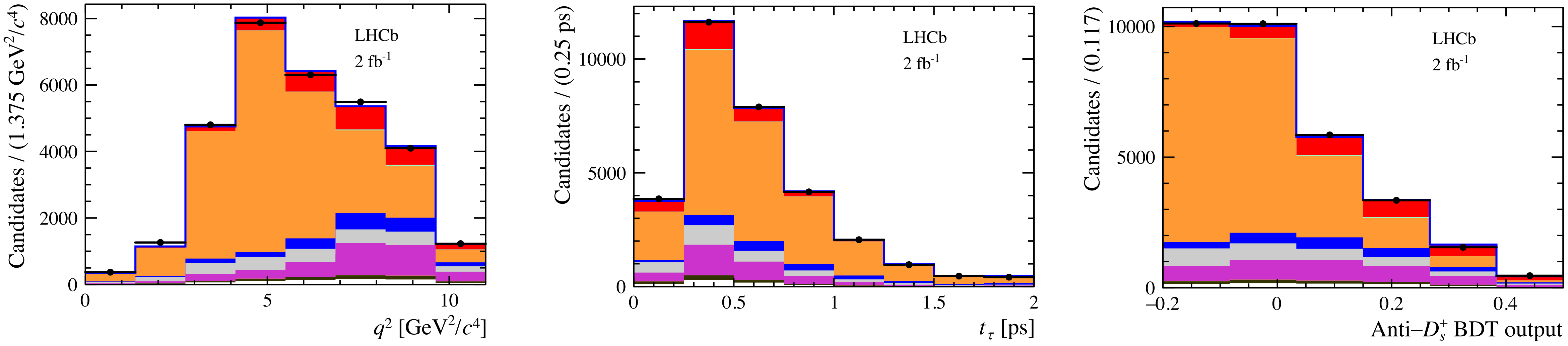
- Specific control samples are used to check and adjust simulation/data agreement for the B→ D_s X production fractions and D decay model.



Phys. Rev. D 108, 012018

R(D*) HADRONIC - RESULTS

- 3D binned template fit on q^2, τ decay-time, anti-D_s BDT output.

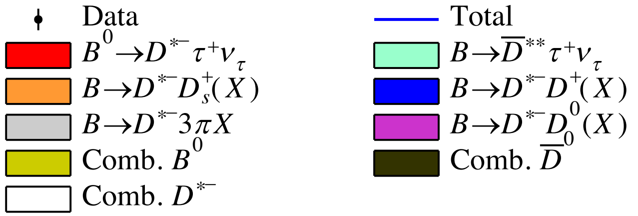


Phys. Rev. D 108, 012018

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

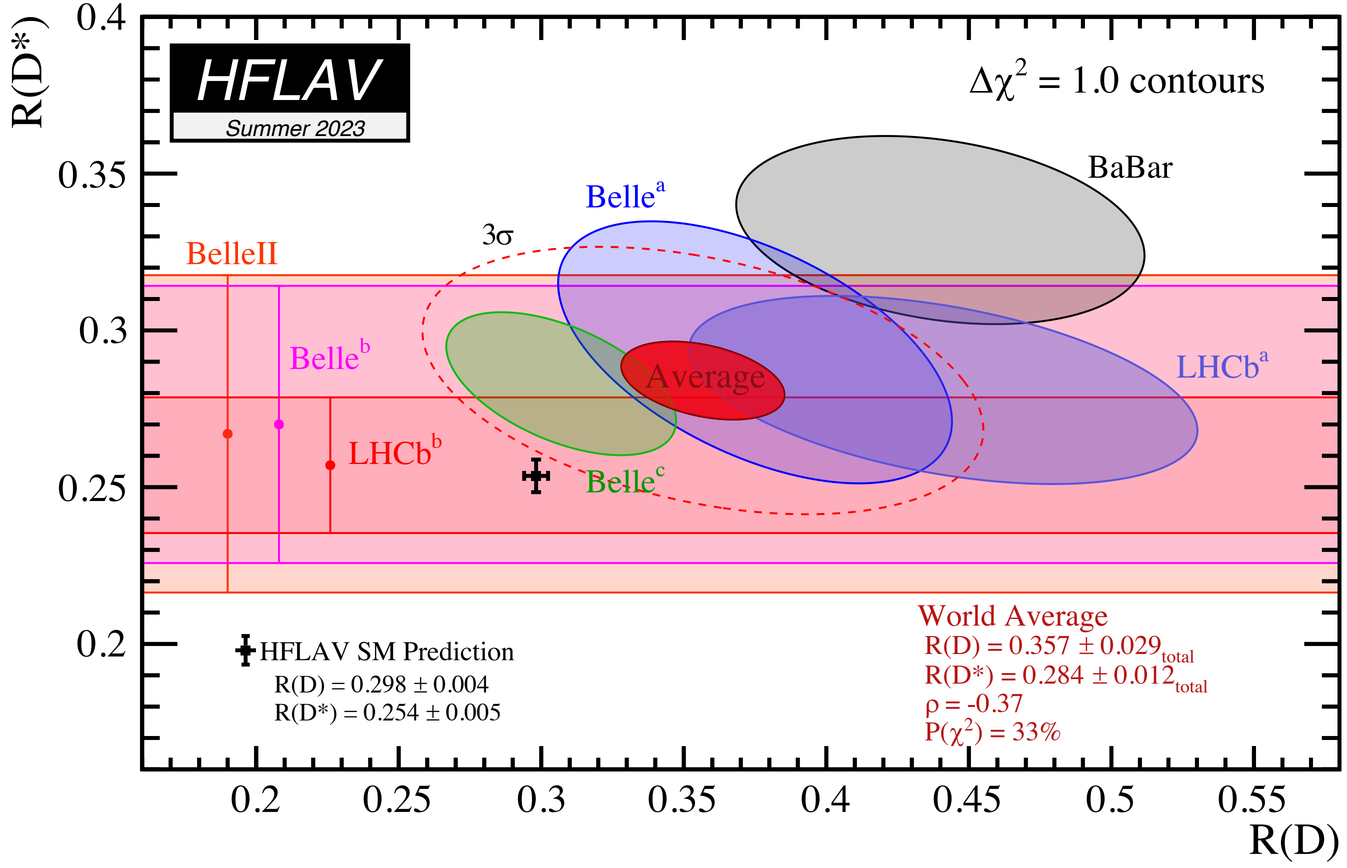
Combined with Run1 result (Phys.Rev. D97,072013)

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



- In agreement with R(D*)-R(D) world-average, 1 σ above the SM prediction.
- Main systematic uncertainties: limited size of simulated samples, signal/background modelling

R(D*)-R(D) world average



- R(D) and R(D*) exceed the SM predictions, by 2.0σ and 2.2σ respectively.
- Combined deviation from SM is about 3.3 σ

→New measurements, in particular of R(D), will be crucial to clarify the tension

Prospects on $R(X_c)$ at LHCb

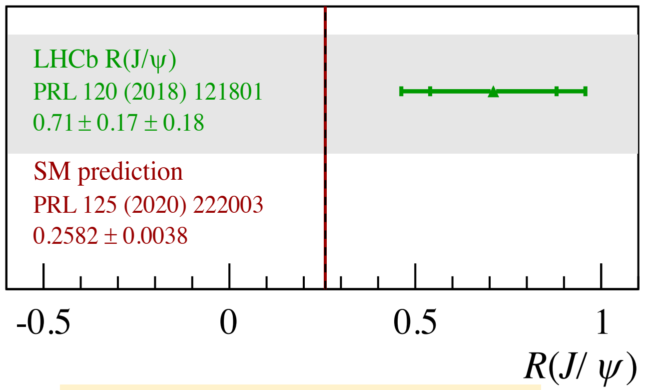
- Hadronic collisions give access to $b\to c l\nu$ transition in all b mesons and baryons

- Measurements in $B_c\to J/\psi\ \tau\nu$ (muonic tau) and $\Lambda_b\to\Lambda_c\ \tau\nu$ (hadronic tau) already pioneered

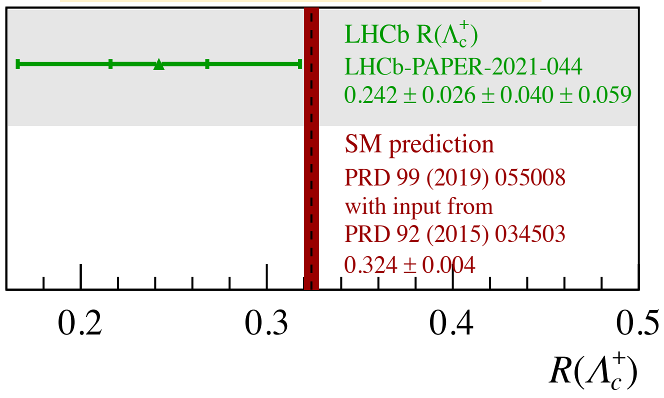
- Currently under study:
  - $B^0\to D^{(*)+}\ l\nu$ and $B_s\to D_s^{(*)}\ l\nu$ decays
  - Other charm mesons and D decay modes
    - D^{**}
    - $D^{*+}\to D^0\pi^+$, $D^0\to K^-3\pi$
    - $D^{*0}\to D^0\ \gamma/\pi^0$

- Full Run2 data sample to be fully exploited (total of 9 fb^{-1})

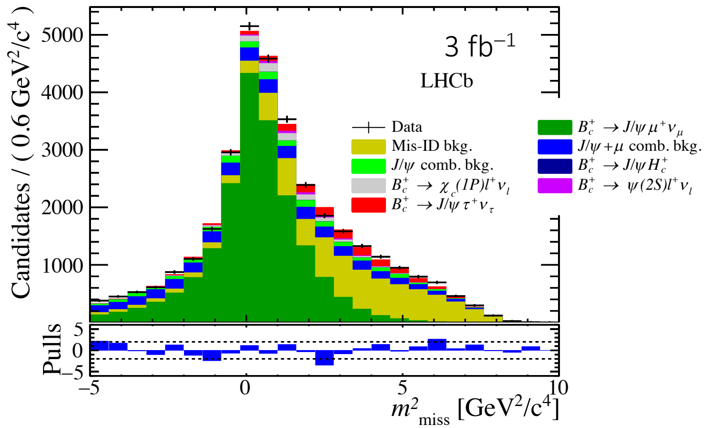
Phys. Rev. Lett. 120, 121801



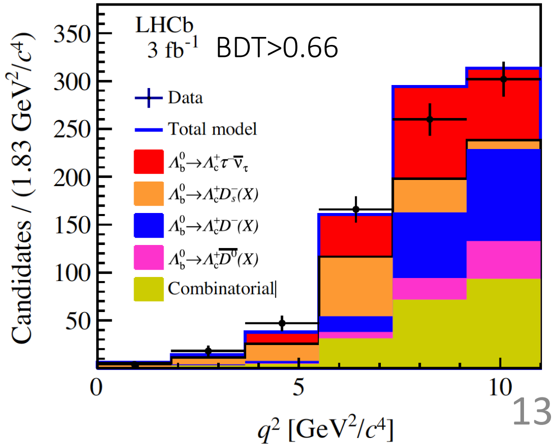
Phys. Rev. Lett. 128, 191803



$B_c\to J/\psi\tau\nu$



$\Lambda_b\to\Lambda_c\tau\nu$

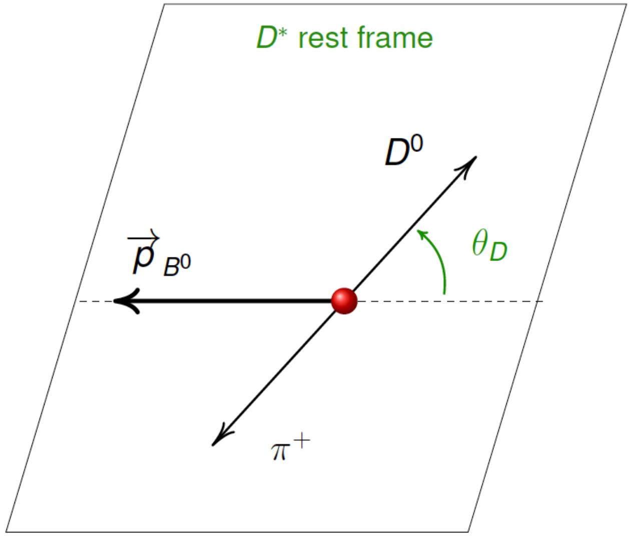


LONGITUDINAL D* POLARIZATION FRACTION IN B→D$^*\tau\nu$ DECAYS

- R(X_c) measurements provide the sensitivity to NP contributions coming from the fully integrated semileptonic branching ratios.
- Additional sensitivity to NP comes from B→D*l ν angular distributions.
- First LHCb angular measurement = D* longitudinal polarization fraction in B→D$^*\tau\nu$.
- Differential decay rate:

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

unpolarized signal fraction (a_{θ_D}) — polarized signal fraction (c_{θ_D})



- Longitudinal polarization fraction

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

PREDICTIONS AND PREVIOUS RESULTS

$B \rightarrow D^* \tau \nu$

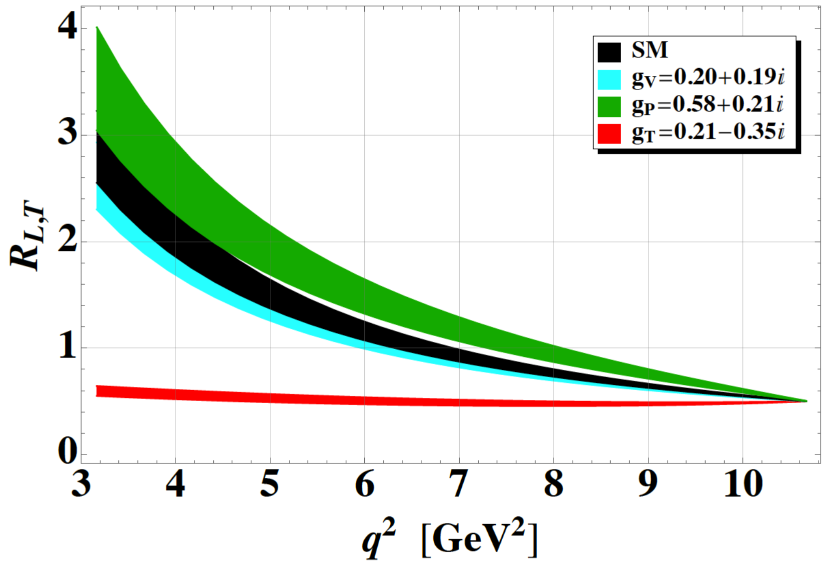
- SM predictions $F_L^{D^*} = 0.441 \pm 0.006$ (arXiv:1808.03565); 0.457 ± 0.010 (arXiv:1805.08222)
- Belle $F_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$ (arXiv:1903.03102)

  in slight tension with SM

- Different predictions in some NP scenarios (arXiv:1907.02257)

$$R_{L,T}(q^2) = \frac{d\Gamma_L/dq^2}{d\Gamma_T/dq^2}$$

$$F_L^D(q^2) = \frac{R_{L,T}(q^2)}{1+R_{L,T}(q^2)}$$



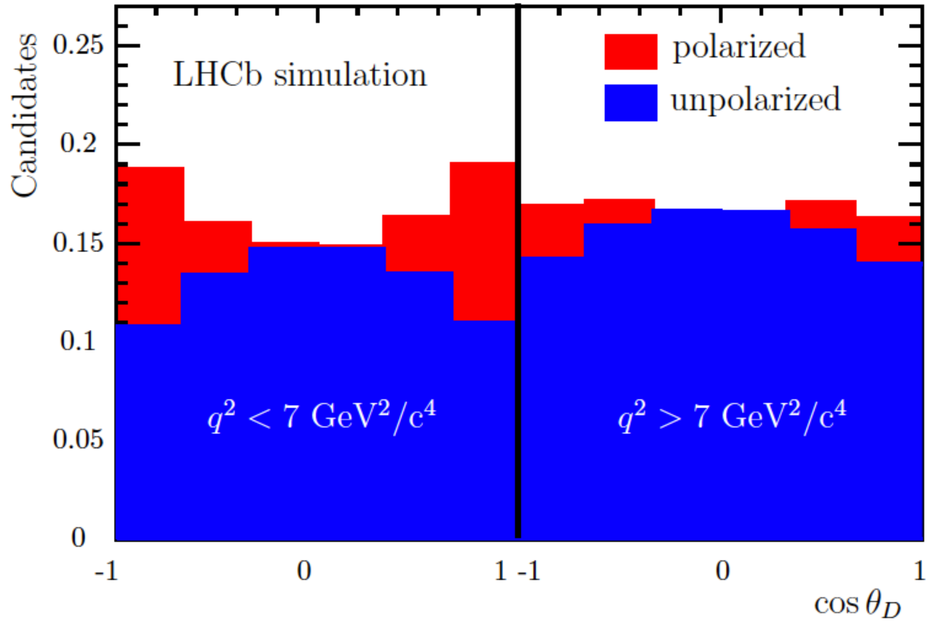
- $F_L^{D^*}$ measurement on electron and muons are currently in agreement

  $\Delta F_L^{D^*} = F_L^{D^*}(\mu) - F_L^{D^*}(e) = 0.034 \pm 0.024 \pm 0.007$ Belle (arXiv:2301.07529)

LHCb MESUREMENT OF $F_L^{D^*}$ IN $B \rightarrow D^* \tau \nu$ DECAYS

LHCb-PAPER-2023-020

- Analysis done with same $\tau \rightarrow 3\pi(\pi^0)\nu_\tau$ sample as the $R(D^*)$ 2015+16 measurement, but simultaneous fit with Run1 data. Total of 5 fb^{-1}.
- Divide data into two q^2 regions ($q^2 \lessgtr 7$ GeV^2/c^4) and add the $\cos\theta_D$ observable.
- Signal template splitted in unpolarized and polarized components.
- Expected $\cos\theta_D$ distribution after reconstruction and selection →



$F_L^{D^*}$ IN $B \to D^* \tau \nu$ DECAYS - BACKGROUND

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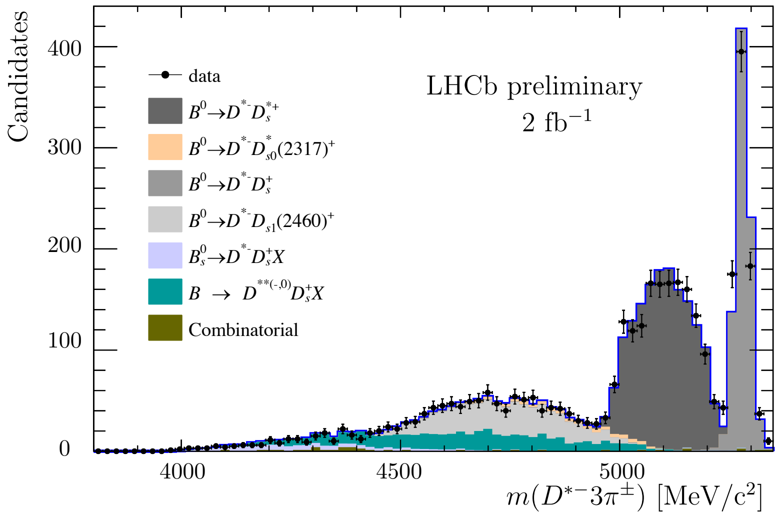
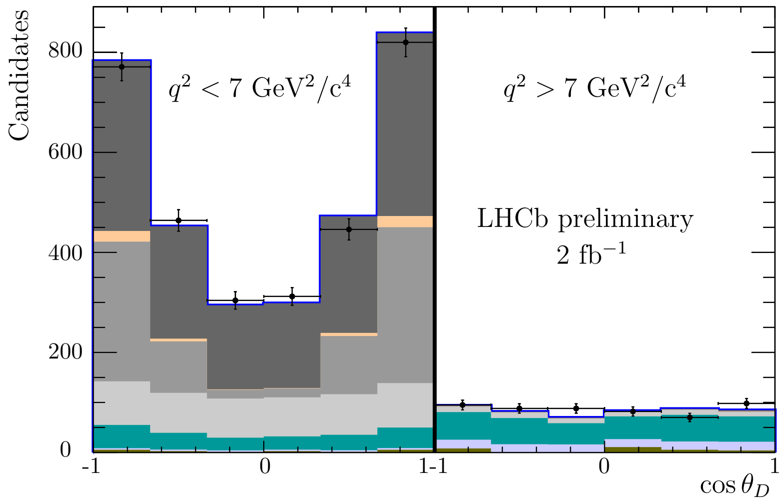
- Dominant $B \to D^{*-} 3\pi^{\pm} X$ «prompt» component and sub-dominat $B \to D^{*-} D X$ «double charm» component reduced with a similar selection as in $R(D^*)$ analysis.
- Simulation templates of residual $B \to D^{*-} D_s X$ component are corrected to adjust $D_s^{(*,**)}$ production fractions and D_s decay models, using specific control samples.
- $B \to D^{*-} D^{0,+}(X)$ templates also adjusted with specific control samples.

$B \to D^{*-} D_s^+ X$





Fractions normalized to $B \to D^{*-} D_s^{*+}$

Parameter	Run1 fit	Run2 fit
$f_{B^0 \to D^{*-} D_s^+}$	0.56 ± 0.05	0.56 ± 0.03
$f_{B^0 \to D^{*-} D_{s0}^{*+}}$	0.01 ± 0.05	0.08 ± 0.04
$f_{B^0 \to D^{*-} D_{s1}'^{+}}$	0.37 ± 0.05	0.44 ± 0.04
$f_{B^{0,\pm} \to D^{*} D_s^+ X}$	0.36 ± 0.07	0.34 ± 0.03
$f_{B_s^0 \to D^{*-} D_s^+ (X)}$	0.07 ± 0.03	0.15 ± 0.04

$F_L^{D^*}$ IN $B \to D^* \tau \nu$ DECAYS - RESULTS

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- 4D-binned template fit simultaneous on Run1 and Run2 data on:

τ^+ decay time, $\cos\theta_D$ in two q^2 bins, anti-D_s BDT output

- $F_L^{D^*}$ determined from the observed signal polarized and unpolarized yields

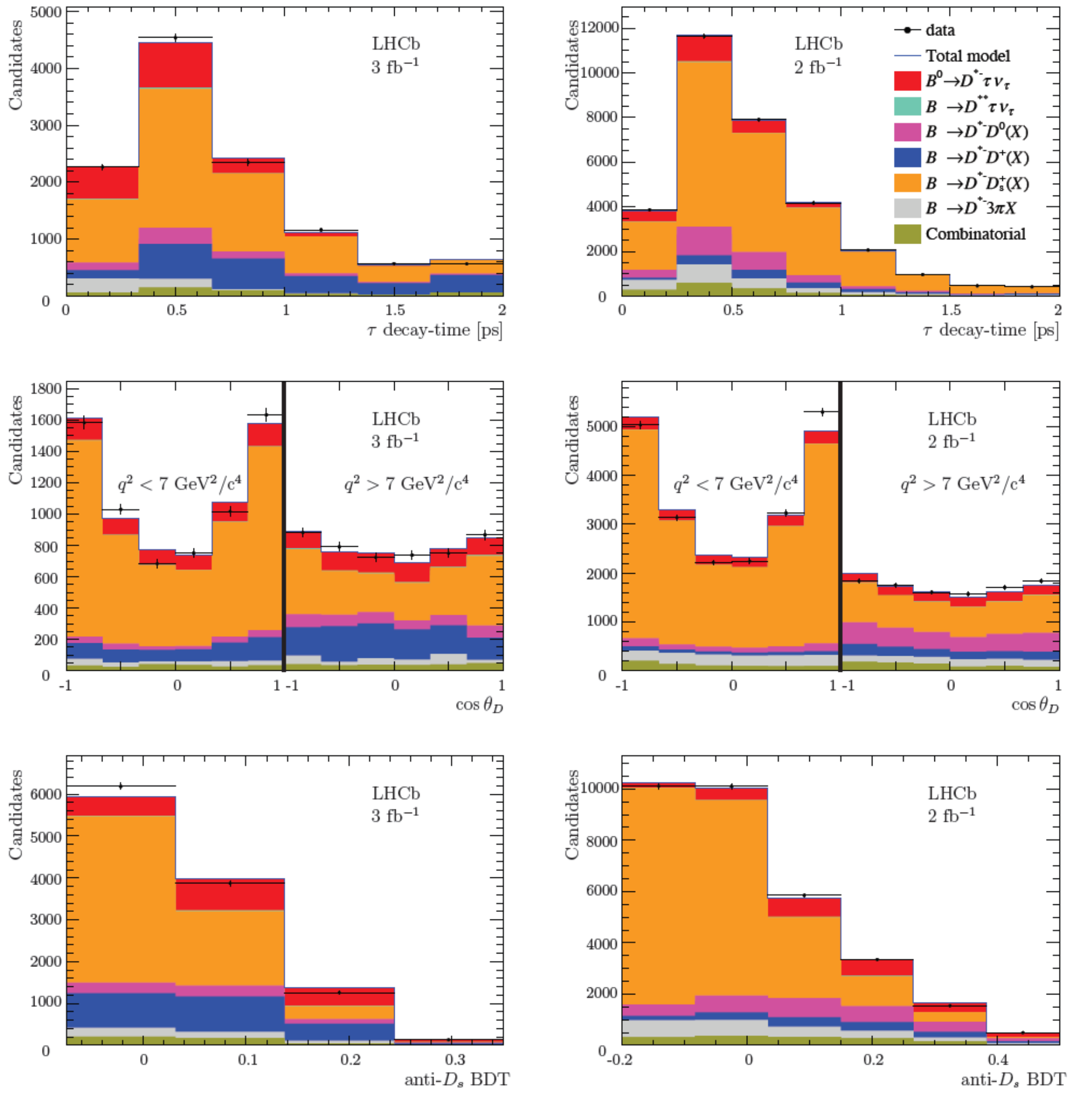
$$q^2 < 7\,\mathrm{GeV}^2/c^4: \quad 0.51 \pm 0.07(stat) \pm 0.03(syst)$$

$$q^2 > 7\,\mathrm{GeV}^2/c^4: \quad 0.35 \pm 0.08(stat) \pm 0.02(syst)$$

$$q^2\text{integrated}: \quad 0.43 \pm 0.06(stat) \pm 0.03(syst)$$

Compatible with SM predictions

- Main systematic from simulated templates statistics, FF parametrization, D_s decay model in background



CONCLUSIONS

- LHCb has measured R(D^*) and R(D) with muonic and hadronic tau decays.
  - World average in 3.3 σ tension with SM prediction.
- Measurements on full Run2 data sample and with other B channels are underway.

- Fraction of longitudinal D* polarization in $B \to D^* \tau \nu$ decays measured in two q^2 bins.
  - Better precision than previous result, compatible with SM prediction.
- Full angular analysis of $B \to D^* l \nu$ decays will provide additional insight in possible NP structure.

- Next steps with larger data sample from LHCb Upgraded Detector in LHC Run3 and 4 and aim for collecting 300 fb^{-1} with further LHCb upgrades.

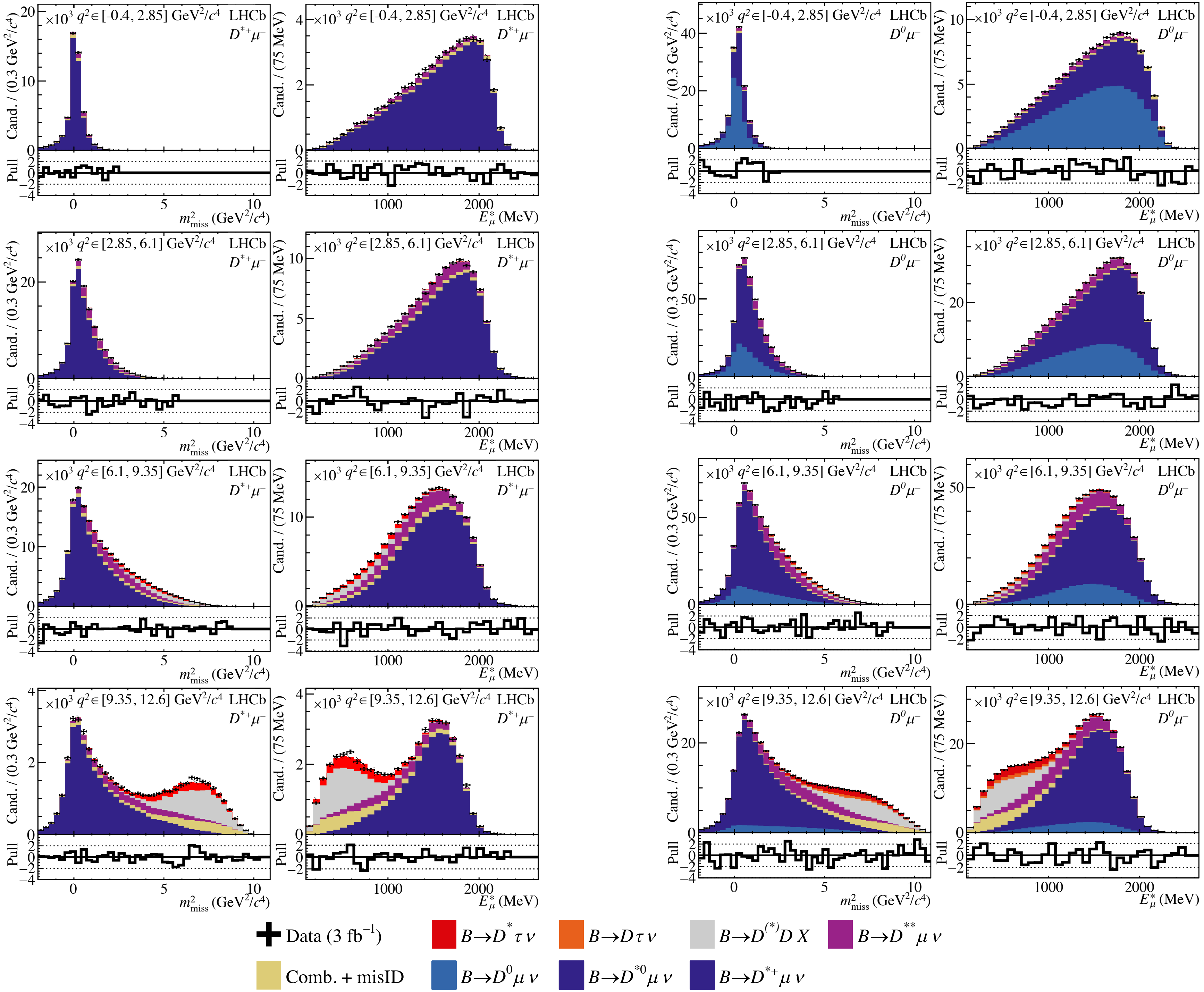
backup

R(D^0) AND R(D^*) WITH MUONIC TAU DECAYS - Systematics

Phys. Rev. Lett. 131, 111802

Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)}(\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)}(\times 10^{-2})$
Statistical uncertainty	1.8	6.0
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
Total uncertainty	3.0	8.9

$D^{*+}\mu^-$



LHCb
$q^2 \in [-0.4, 2.85]$ GeV$^2/c^4$
$q^2 \in [2.85, 6.1]$ GeV$^2/c^4$
$q^2 \in [6.1, 9.35]$ GeV$^2/c^4$
$q^2 \in [9.35, 12.6]$ GeV$^2/c^4$
$D^{*+}\mu^-$
$D^0\mu^-$
Cand. / (0.3 GeV$^2/c^4$)
Cand. / (75 MeV)
Pull
$m^2_{\rm miss}$ (GeV$^2/c^4$)
E^*_μ (MeV)
Data (3 fb^{-1})
$B \to D^* \tau \nu$
$B \to D \tau \nu$
$B \to D^{(*)} D X$
$B \to D^{**} \mu \nu$
Comb. + misID
$B \to D^0 \mu \nu$
$B \to D^{*0} \mu \nu$
$B \to D^{*+} \mu \nu$

$D^0\mu^-$

R(D*) WITH HADRONIC TAU DECAYS - Systematics

Phys. Rev. D 108, 012018

TABLE V. Summary of relative systematic uncertainties on the ratio $\mathcal{K}(D^{*-})$.

Source	Systematic uncertainty (%)
Signal decay template shape	1.8
Signal decay efficiency	0.9
Fractions of signal τ^+ decays	0.3
Possible contributions from other τ^+ decays	1.0
Fixing the $\bar{D}^{**}\tau^+\nu_\tau$ and $D_s^{**+}\tau^+\nu_\tau$ fractions	$^{+1.8}_{-1.9}$
Normalization mode PDF choice	1.0
Knowledge of the $D_s^+ \to 3\pi X$ decay model	1.0
Specifically the $D_s^+ \to a_1 X$ fraction	1.5
$B \to D^{*-}D_s^+(X)$ template shapes	0.3
$B \to D^{*-}D^0(X)$ template shapes	1.2
$B \to D^{*-}D^+(X)$ template shapes	$^{+2.2}_{-0.8}$
Fixing $B \to D^{*-}D_s^+(X)$ background model parameters	1.1
Fixing $B \to D^{*-}D^0(X)$ background model parameters	1.5
$B \to D^{*-}3\pi X$ template shapes	1.2
Combinatorial background normalization	$^{+0.5}_{-0.6}$
PID efficiency	0.5
Kinematic reweighting	0.7
Vertex error correction	0.9
Normalization mode efficiency [modeling of $m(3\pi)$]	1.0
Preselection efficiency	2.0
Signal efficiency (size of simulation sample)	1.1
Normalization efficiency (size of simulation sample)	1.1
Empty bins in templates	1.3
PDF shapes uncertainty (size of simulation sample)	2.0
Total systematic uncertainty	$^{+6.2}_{-5.9}$
Total statistical uncertainty	5.9

$F_L^{D^*}$ IN $B \rightarrow D^* \tau \nu$ DECAYS – Results and Systematics

LHCb-PAPER-2023-020

Parameter	$q^2 < 7\,\mathrm{GeV}^2/c^4$	$q^2 > 7\,\mathrm{GeV}^2/c^4$	integrated
$F_L^{D^*}$	0.510 ± 0.068	0.348 ± 0.082	0.427 ± 0.059
$a_{\theta_D}(q^2)$	0.122 ± 0.022	0.147 ± 0.032	0.143 ± 0.030
$c_{\theta_D}(q^2)$	0.133 ± 0.052	0.005 ± 0.020	0.070 ± 0.058

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
fSignal0	0.001	0.001	0.001
fSignalDstst	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
$\cos\theta_D$ $D^{*-}D_s^+X$	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