Lepton flavour universality violating B decays in trees

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XIII Meeting on B Physics
Marseille, 2nd October, 2018

Introduction

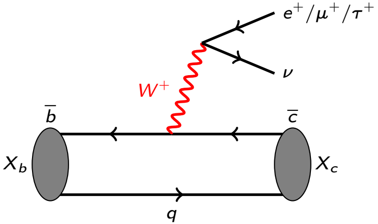
Lepton Flavour Universality (LFU):

- In SM, electroweak couplings of charged leptons are identical (universal).
- Difference between e, μ and τ should therefore only be driven by mass.
- Test: ratios of branching fractions to final states differing by lepton flavour.

LFU tests with tree-level b-hadron decays:

$$R(X_c) = \frac{\mathcal{B}(X_b \to X_c \tau^+ \nu_\tau)}{\mathcal{B}(X_b \to X_c \ell^+ \nu_\ell)}.$$

- X_b: b-hadron
- X_c: c-hadron
- ℓ^+: average e^+ & μ^+ or just μ^+



Introduction

In this talk:

- BaBar $R(D)$–$R(D^*)$ hadronic tag, leptonic τ
- Belle $R(D)$–$R(D^*)$ hadronic tag, leptonic τ
- Belle $R(D^*)$ semileptonic tag, leptonic τ
- LHCb $R(D^*)$ muonic τ
- LHCb $R(J/\psi)$ muonic τ
- Belle $R(D^*)$ 1-prong hadronic τ ($+$ τ polarisation)
- LHCb $R(D^*)$ 3-prong hadronic τ

Predictions:

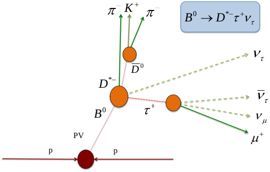
- $R(D) = 0.299 \pm 0.003$ [HFLAV Summer 2018]
- $R(D^*) = 0.258 \pm 0.005$ [HFLAV Summer 2018]
- $R(J/\psi) \in [0.25, 0.28]$ [PLB452 (1999) 120, arXiv:0211021, PRD73 (2006) 054024, PRD74 (2006) 074008]

Leptonic τ modes

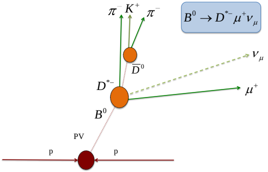
Introduction to B-factory measurements

B-factory measurements:

$$R(D^{(*)}) = \frac{\mathcal{B}(\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau)}{[\mathcal{B}(\overline{B} \to D^{(*)}e^-\overline{\nu}_e) + \mathcal{B}(\overline{B} \to D^{(*)}\mu^-\overline{\nu}_\mu)]/2}$$



- Use $\tau^- \to e^-\overline{\nu}_e\nu_\tau$ and $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ so normalisation modes have same visible final states
- Charged and neutral B and $D^{(*)}$ mesons
- D and D^* reconstructed in many final states



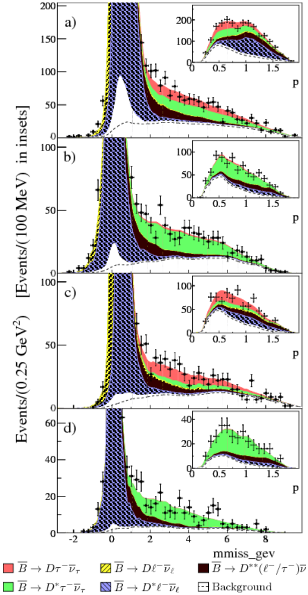
BaBar $R(D)$–$R(D^*)$ with hadronic tag

- Reconstruct hadronic decays of other B ($=B_{\text{tag}}$) + $D^{(*)}$ + $\ell(=e,\mu)$
- Yields determined from 2D fit:
  - $m^2_{\text{miss}} \equiv |P_{e^+e^-} - P_{B_{\text{tag}}} - P_{D^{(*)}} - P_\ell|^2$
  - $|\mathbf{p}^*_\ell| \equiv$ momentum of ℓ in B frame

$$R(D) = 0.440 \pm 0.058\,(\text{stat}) \pm 0.042\,(\text{syst})$$

$$R(D^*) = 0.332 \pm 0.024\,(\text{stat}) \pm 0.018\,(\text{syst})$$

- $R(D)$ 2.0σ above SM
- $R(D^*)$ 2.7σ above SM
- Combination 3.4σ from SM



[PRL 109, 101802 (2012)]

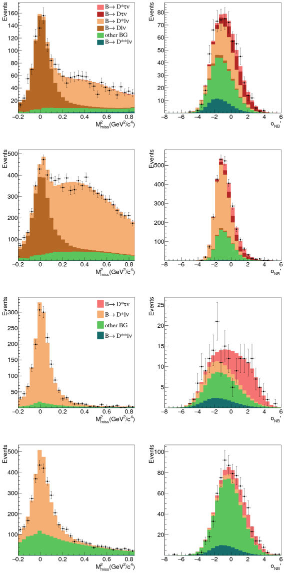
Belle $R(D)$–$R(D^*)$ with hadronic tag

- Reconstruct hadronic decays of other B ($=B_{\text{tag}}$) + $D^{(*)}$ + $\ell(=e,\mu)$
- Yields determined from simultaneous 1D fits:
  - m^2_{miss} for $m^2_{\text{miss}} < 0.85\,\text{GeV}/c^2$
  - Neural network output for $m^2_{\text{miss}} > 0.85\,\text{GeV}/c^2$, trained to distinguish $\overline{B} \to D^{(*)}\tau^-\overline{\nu}_\tau$ from backgrounds

$$R(D) = 0.375 \pm 0.064\,(\text{stat}) \pm 0.029\,(\text{syst})$$

$$R(D^*) = 0.293 \pm 0.038\,(\text{stat}) \pm 0.015\,(\text{syst})$$

- Combination 1.8σ from SM, 1.4σ from BaBar result



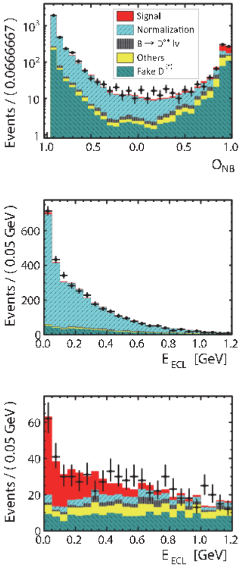
[PRD 92, 072014 (2015)]

Belle $R(D^*)$ with semileptonic tag

- Reconstruct $B^0{}_{\text{tag}} \to D^{*+}\ell^-\overline{\nu}_\ell$ along with $B^0{}_{\text{sig}} \to D^{*+}\ell^-\overline{\nu}_\ell$ or $D^{*+}\tau^-\overline{\nu}_\tau$
- Yields determined 2D fit:
    - $E_{\text{ECL}} \equiv$ energy in ECAL not associated with reconstructed B
    - Neural network output, trained to distinguish $D^*\tau\nu$ from $D^*\ell\nu$

$$R(D^*) = 0.302 \pm 0.030\,(\text{stat}) \pm 0.011\,(\text{syst})$$

- 1.6σ above SM



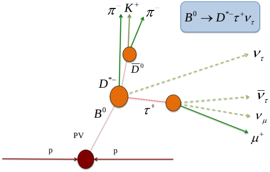
[PRD 94, 072007 (2016)]

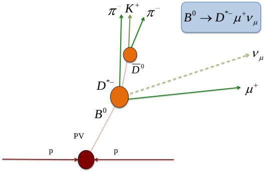
Introduction to LHCb measurements

LHCb measurements:

$$R(X_c) = \frac{\mathcal{B}(X_b \to X_c \tau^+ \nu_\tau)}{\mathcal{B}(X_b \to X_c \mu^+ \nu_\mu)}$$

- Same visible final state $X_c \mu^+$





LHCb $R(D^*)$ muonic: introduction

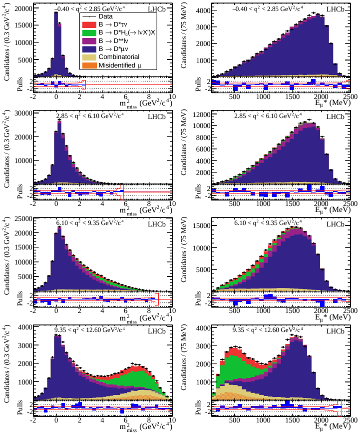
$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

- Both modes have same visible final state: $D^{*-}\mu^+$.
- Neither fully reconstructable, due to neutrinos.
  - B^0 momentum approximated using B^0 decay vertex and scaling visible longitudinal momentum by $m(B^0)/m(D^{*-}\mu^+)$
  - Resolution on kinematic variables enough to distinguish between τ/μ modes.
- 3D binned template fit to extract yields:
  - $q^2 \equiv |P_{B^0} - P_{D^*}|^2$,
  - $m^2_{\text{miss}} \equiv |P_{B^0} - P_{D^*} - P_{\mu^+}|^2$,
  - $E^*_{\mu^+} \equiv$ muon energy in B^0 rest frame.

LHCb $R(D^*)$ muonic: fit and result

$$R(D^*) = 0.336 \pm 0.027\,(\text{stat}) \pm 0.030\,(\text{syst})$$

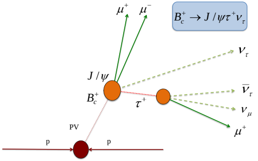
- $1.9\,\sigma$ above SM
- Largest systematics: simulated sample size and mis-ID μ template



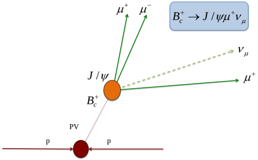
[PRL 115, 112001 (2015)]

LHCb $R(J/\psi)$ muonic: introduction

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\, \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\, \mu^+ \nu_\mu)}$$



- Both modes have same visible final state: $J/\psi\, \mu^+$.
- 3D binned template fit to extract yields:
  - B_c^+ decay time,
  - m^2_{miss},
  - $Z(E^*_{\mu^+}, q^2) \equiv$ flattened 4×2 histogram of $E^*_{\mu^+}$, q^2.
- B_c^+ decay form factors not precisely determined; constrained experimentally from this analysis.
- Low rate of B_c^+ production, but no long-lived D-meson background.

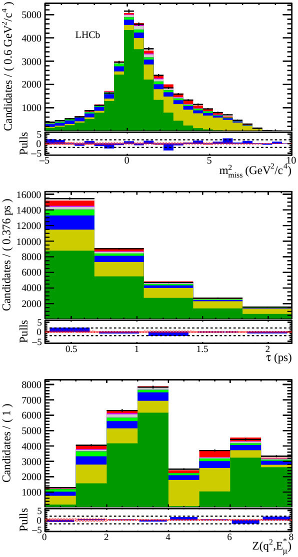


LHCb $R(J/\psi)$ muonic: fit and result

- First evidence of the decay $B_c^+ \to J/\psi\,\tau^+\nu_\tau$ ($3\,\sigma$ significance).

$$R(J/\psi) = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$$

- $2\,\sigma$ above the SM.
- Largest systematics: $B_c^+ \to J/\psi$ form factors and MC statistics



[PRL 120, 121801 (2018)]

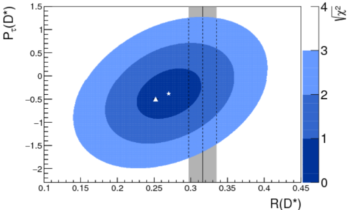
Hadronic τ modes

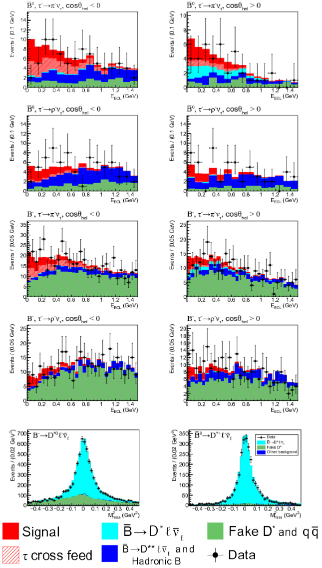
Belle $R(D^*)$ 1-prong hardonic and τ^- polarisation

- Using $\tau^- \to \pi^- \nu_\tau$ and $\tau^- \to \rho^- \nu_\tau$
- Reconstruct hadronic mode of other B (B_{tag}) + D^* + τ/ℓ
- $\overline{B} \to D^* \tau^- \overline{\nu}_\tau$ yield from simultaneous fit to E_{ECL} in different signs of $\cos\theta_h$, B species and τ^- decay
- $\overline{B} \to D^* \ell \overline{\nu}_\ell$ yield from fitting m^2_{miss}

$$R(D^*) = 0.270 \pm 0.035\,(\text{stat})^{+0.028}_{-0.025}\,(\text{syst})$$

$$P_\tau(D^*) = -0.38 \pm 0.51\,(\text{stat})^{+0.21}_{-0.16}\,(\text{syst})$$





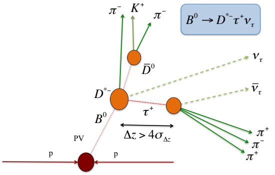
[PRD 97, 012004 (2018)]

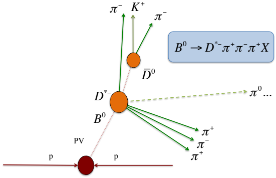
LHCb $R(D^*)$ 3-prong hadronic: introduction

$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi^\pm)} = \frac{N_{\text{sig}}}{N_{\text{norm}}}\frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}}\frac{1}{\mathcal{B}(\tau^+ \to 3\pi^\pm(\pi^0)\overline{\nu}_\tau)}$$

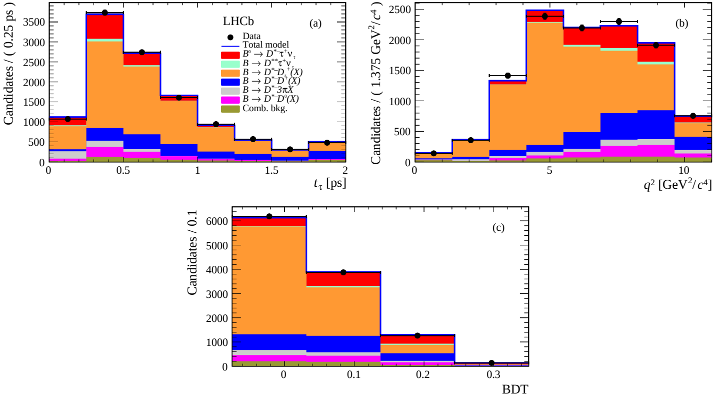
- Signal and normalisation same visible final state: $D^{*-}3\pi^\pm$.
- N_{sig} from 3D binned template fit:
  - $q^2 \equiv |P_{B^0} - P_{D^*}|^2$,
  - τ^+ decay time,
  - Output of BDT trained to discriminate signal from $D^* D_s^+$.
- N_{norm} from unbinned max likelihood fit to $m(D^* 3\pi^\pm)$.
- Make use of three-prong tau vertex in selection.
- Convert $\mathcal{K}(D^*)$ to $R(D^*)$:

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





LHCb $R(D^*)$ 3-prong hadronic: fit and result



[PRL 120, 171802 (2018), PRD 97, 072013 (2018)]

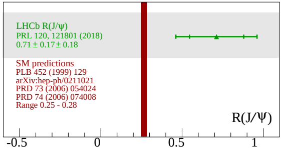
$$\mathcal{K}(D^*) = 1.97 \pm 0.13\,(\text{stat}) \pm 0.18\,(\text{syst})$$

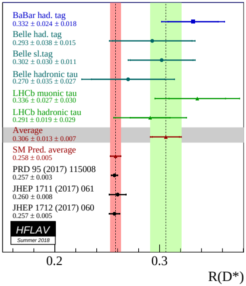
$$R(D^*) = 0.291 \pm 0.019\,(\text{stat}) \pm 0.026\,(\text{syst}) \pm 0.013\,(\text{ext}).$$

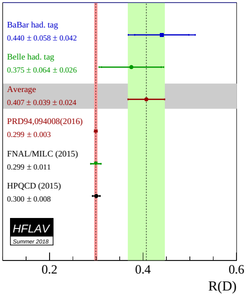
- $0.9\,\sigma$ above SM, compatible with experimental average.

Averages

World averages





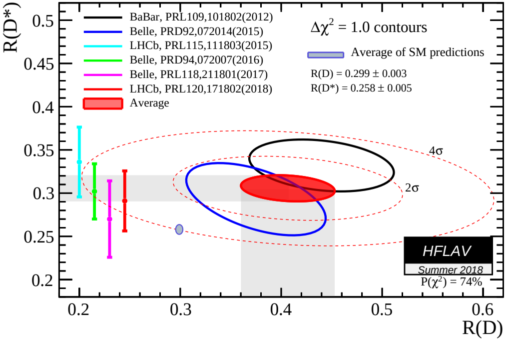


- $6 \times R(D^*)$, $2 \times R(D)$, $1 \times R(J/\psi)$.
- All lie above the SM expectation.

[HFLAV Summer 2018]

World averages

- HFLAV summer 2018 $R(D)$–$R(D^*)$ average is 3.8 σ from the SM.
- Reduction from 4.1 σ due to increase in theory uncertainties.



[HFLAV Summer 2018]

Conclusions and prospects

- Hints of LFU violation in semitauonic B decays.
  - $R(D)$–$R(D^{*})$: $3.8\,\sigma$ away from SM.
  - $R(J/\psi)$: $2\,\sigma$ above SM.
- BaBar and Belle results statistics dominated
  - Improved precision from Belle II
- LHCb results only use Run 1 data: Runs 2,3,4... will bring much larger statistics.
- LHCb results systematics-dominated
  - Many systematics will reduce with more data and more MC
  - Others will reduce with improved external measurements (BESIII, Belle II)
- LHCb plans: analyses of more modes
  - $b \to c\tau^{-}\overline{\nu}_{\tau}$: $R(D^{+})$, $R(D^{0})$, $R(D_{s}^{+(*)})$, $R(\Lambda_{c}^{+(*)})$ ...
  - $b \to u\tau^{-}\overline{\nu}_{\tau}$: $\Lambda_{b}^{0} \to p\tau^{-}\overline{\nu}_{\tau}$, $B^{+} \to p\overline{p}\tau^{+}\nu_{\tau}$ ...
- New observables beyond ratios of branching fractions, *e.g.* angular analyses to discriminate between NP models.

Backup slides

Tau branching fractions

Mode	BF (%)
$\tau^- \to \pi^-\pi^0\nu_\tau$	25.49 ± 0.09
$\tau^- \to e^-\overline{\nu}_e\nu_\tau$	17.82 ± 0.04
$\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$	17.39 ± 0.04
$\tau^- \to \pi^-\nu_\tau$	10.82 ± 0.05
$\tau^- \to 3\pi^{\mp}\nu_\tau$	9.31 ± 0.05
$\tau^- \to 3\pi^{\mp}\pi^0\nu_\tau$	4.62 ± 0.05

[PDG]

LHCb $R(D^*)$ muonic systematics

- MC statistics largest systematic.
- Mis-ID μ template: reduce with improved rejection and more sophisticated technique.

Source	$\delta R(D^*)[\times 10^{-2}]$
Simulated sample size (model)	2.0
Misidentified μ template shape	1.6
$\bar{B}^0 \to D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors	0.6
$\bar{B} \to D^{*+}X_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{**}\mu^-\nu_\mu)$	0.5
$\bar{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\bar{B} \to D^{**}(\to D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors	0.3
$\bar{B} \to D^{*+}(D_s^+ \to \tau\nu)X$ fraction	0.1
Simulated sample size (normalisation)	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form-factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$	< 0.1
Total systematic uncertainty	3.0

[PRL 115, 112001 (2015)]

LHCb $R(J/\psi)$ systematics

- B_c^+ form factors: recent improvements should enter into updated measurement.
- MC statistics second-largest systematic.

Source	$\delta R(J/\psi)[\times 10^{-2}]$
Simulation sample size	8.0
$B_c^+ \to J/\psi$ form factors	12.1
$B_c^+ \to \psi(2S)$ form factors	3.2
Bias correction	5.4
$B_c^+ \to J/\psi X_c X$ cocktail composition	3.6
Z binning strategy	5.6
Misidentification background strategy	5.4
Combinatorial background cocktail	4.5
Combinatorial J/ψ sideband scaling	0.9
Empirical reweighting	1.6
Semitauonic $\psi(2S)$ and χ_c feed-down	0.9
Fixing $A_2(q^2)$ slope to zero	0.3
Efficiency ratio	0.6
$\mathcal{B}(\tau^+ \to \mu^+ \nu_\mu \overline{\nu}_\tau)$	0.2
Total systematic uncertainty	17.7

[PRL 120, 121801 (2018)]

LHCb $R(D^*)$ hadronic systematics

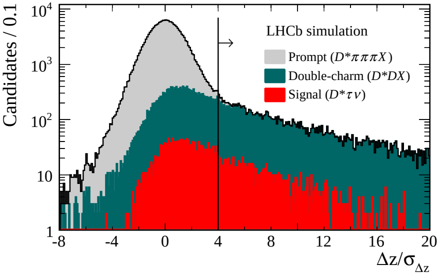
- Largest systematic uncertainty is MC statistics.
- Uncertainties on double charm backgrounds should improve with more data and improved external measurements.
- Uncertainty on efficiency ratio should improve with more statistics.

Source	$\frac{\delta R(D^*)}{R(D^*)}$ [%]
Simulated sample size	4.7
Empty bins in templates	1.3
Signal decay model	1.8
$D^{**}\tau\nu_\tau$ and $D_s^{**}\tau\nu_\tau$ feed-down	2.7
$D_s^+ \to 3\pi^\pm X$ decay model	2.5
$B \to D^* D_s^+ X$, $D^* D^+ X$, $D^* D^0 X$ backgrounds	3.9
Combinatorial background	0.7
$B \to D^{*-} 3\pi^\pm X$ background	2.8
Efficiency ratio	3.9
Normalisation channel efficiency (modelling of $B^0 \to D^{*-} 3\pi^\pm$)	2.0
Total systematic uncertainty	9.1

[PRL 120, 171802 (2018), PRD 97, 072013 (2018)]

LHCb $R(D^*)$ hadronic backgrounds

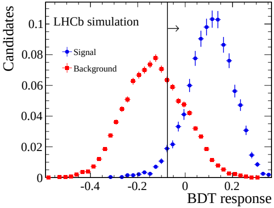
- Most abundant background: $X_b \to D^{*-}3\pi^{\pm}X$.
  - $\sim 100\times$ more abundant than signal.
  - Suppressed by requiring τ^+ vertex to be $4\sigma_{\Delta z}$ downstream from B vertex.
  - Improves S/B by factor 160.
- Remaining backgrounds: double charm modes with non-negligible lifetimes:
  - $X_b \to D^* D_s^+ X \sim 10\times$ signal,
  - $X_b \to D^* D^+ X \sim 1\times$ signal,
  - $X_b \to D^* D^0 X \sim 0.2\times$ signal.



[PRD 97, 072013 (2018)]

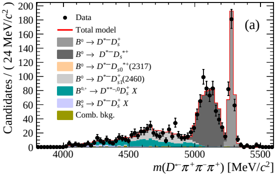
LHCb $R(D^*)$ hadronic backgrounds

Discriminate between signal and double charm backgrounds using a BDT that exploits the resonant structures in the $3\pi^\pm$ systems from τ^+ and D_s^+ decays.



[PRD 97, 072013 (2018)]

Control samples of $D^* D_s^+ X$, $D^* D^+ X$ and $D^* D^0 X$ used to correct simulation.



[PRL 120, 171802 (2018), PRD 97, 072013 (2018)]