Lepton flavour universality in $b \to c$ transitions

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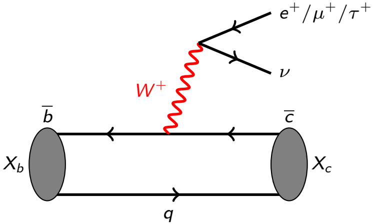
Introduction

Lepton Flavour Universality (LFU):

- In SM, electroweak couplings of charged leptons are universal.
- Difference between e, μ and τ should only be driven by mass.
- Ratios of branching fractions to final states with different leptons.

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 of e^+ & μ^+ or just μ^+

Recent developments in $B \to D^{(*)}$ FFs

Two form-factor parametrisations: BGL [PLB 353, 306 (1995)] and CLN [Nucl.Phys.B 530, 153 (1998)]

- CLN uses HQET constraints (up to $\mathcal{O}(1/m_c)$).
- BGL provides a model-independent parametrisation

2017

- Belle released unfolded $B \to D^{(*)}$ data [PRD 93, 032006 (2016), arXiv:1702.01521]
- Theorists performed fits [PLB 04, 022 (2017) PLB 05, 078 (2017) JHEP 12, 060 (2017)]
    - $|V_{cb}|$ from BGL found to agree better with inclusive measurements
    - $|V_{cb}^{\mathrm{BGL}}| = (4.17 \pm 0.21)\%$
    - $|V_{cb}^{\mathrm{CLN}}| = (3.82 \pm 0.15)\%$

2018

- Belle update with more data [arXiv:1809.03290]
- $|V_{cb}|$ from BGL & CLN compatible, but more like old result $(3.96^{+0.11}_{-0.10}\%)$ [PLB 06, 039 (2019)]
- Errors improved but still not perfect

Recent developments in $B \to D^{(*)}$ FFs

New (2019):

- Predictions of $R(D^{(*)})$ and polarisations with modified CLN [arXiv:1908.09398]
  - Unitarity bounds [PLB 353, 306 (1995), JHEP 12, 060 (2017)]
  - LQCD for $f_{+,0}(q^2)$ $(B \to D)$, $h_{A_1}(q^2_{\max})$ $(B \to D^*)$ [PRD 92, 034506 (2015),PRD 93, 119906 (2015),PRD 97, 054502 (2018),PRD 98, 114504 (2014),EPJC 77, 112 (2017)]
  - LCSR for all FFs but f_T [JHEP 01, 150 (2019)]
  - New: HQET calculations to higher order $(\mathcal{O}(\alpha_s, 1/m_b, 1/m_c^2))$ [arXiv:1908.09398]
  - Errors taken properly into account

$|V_{cb}| = (4.00 \pm 0.11)\%$

$$\boxed{R(D) = 0.298 \pm 0.003} \quad \boxed{R(D^*) = 0.247 \pm 0.006}$$

$$\boxed{P_\tau(D) = 0.321 \pm 0.003} \quad \boxed{P_\tau(D^*) = -0.488 \pm 0.018}$$

$$\boxed{F_L(D^*) = 0.470 \pm 0.012}$$

See [M. Jung's talk at LHCb Implications]

Upcoming: lattice analyses of four of the $B \to D^{(*)}$ FFs at nonzero recoil [arXiv:1906.01019, arXiv:1811.00794, arXiv:1812.07675]

LHCb measurements with muonic τ decays

LHCb measurements:

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

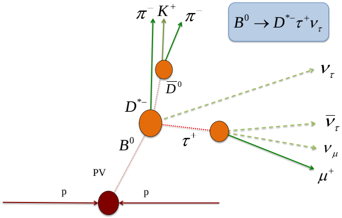
- Same visible final state $X_c \mu^+$
- 3D binned template fit to extract yields:
  - $q^2 \equiv |P_{B^0} - P_{D^*}|^2$,
  - $m^2_{\text{miss}} \equiv |P_{B^0} - P_{D^*} - P_{\mu^+}|^2$,
  - $E^*_{\mu^+} \equiv$ muon energy in B^0 rest frame.
  - B_c^+ decay time for $R(J/\psi) \to$ flatten q^2, $E^*_{\mu^+}$

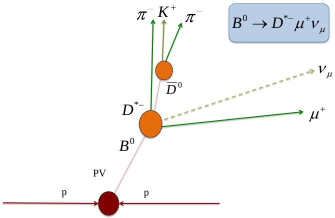
$$\boxed{R(D^*) = 0.336 \pm 0.027 \pm 0.030}$$

[PRL 115, 112001 (2015)]

$$\boxed{R(J/\psi) = 0.71 \pm 0.17 \pm 0.18}$$

[PRL 120, 121801 (2018)]



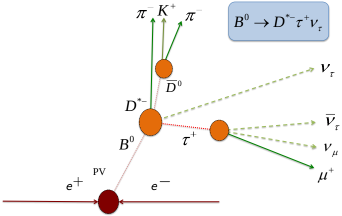


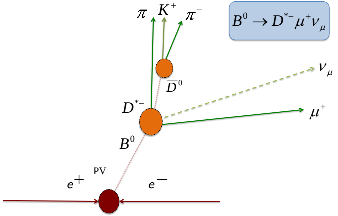
B-factory measurements with leptonic τ decays

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





B-factory measurements with leptonic τ decays

Hadronic B-tag method:

- Reconstruct hadronic decays of other B $(=B_{\text{tag}})$ + $D^{(*)}$ + $\ell(=e,\mu)$
- BaBar: 2D fit [PRD 88, 072012 (2013)]
  - $m^2_{\text{miss}} \equiv |P_{e^+e^-} - P_{B_{\text{tag}}} - P_{D^{(*)}} - P_\ell|^2$
  - $|\mathbf{p}^*_\ell| \equiv$ momentum of ℓ in B frame

$$\boxed{R(D) = 0.440 \pm 0.058 \pm 0.042} \quad \boxed{R(D^*) = 0.332 \pm 0.024 \pm 0.018}$$

- Belle: simultaneous 1D fits [PRD 92, 072014 (2015)]
  - m^2_{miss} for $m^2_{\text{miss}} < 0.85\,\mathrm{GeV}/c^2$
  - Neural network output for $m^2_{\text{miss}} > 0.85\,\mathrm{GeV}/c^2$

$$\boxed{R(D) = 0.375 \pm 0.064 \pm 0.029} \quad \boxed{R(D^*) = 0.293 \pm 0.038 \pm 0.015}$$

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

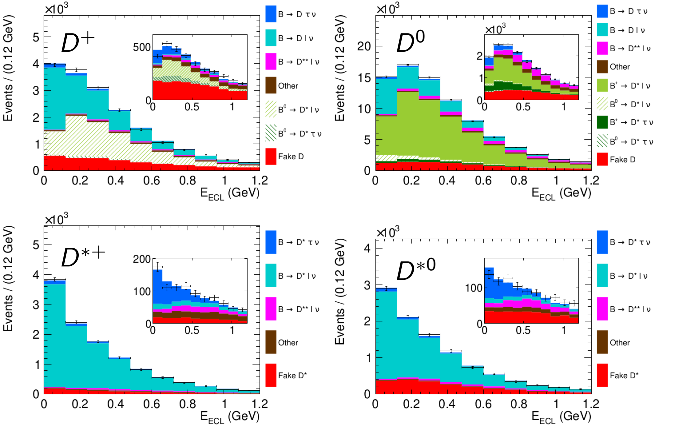
- New (2019) result

  arXiv:1910.05864 (Submitted to PRL)

- 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 from 2D fit:

- $E_{\text{ECL}} \equiv$ energy in ECAL not associated with reconstructed B
- BDT output, trained to distinguish $D^{(*)}\tau\nu$ from $D^{(*)}\ell\nu$



E_{ECL} projections. Inset: BDT$>$ 0.9

$$R(D) = 0.307 \pm 0.037 \pm 0.016$$

$$R(D^*) = 0.283 \pm 0.018 \pm 0.014$$

Measurements with hadronic τ decays

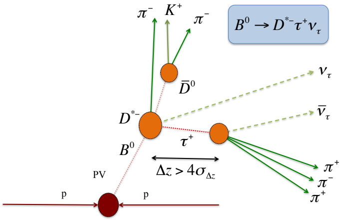
Belle $R(D^*)$ 1-prong [PRL 118, 211801 (2017)] [PRD 97, 012004 (2018)]

- 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: 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}

$$\boxed{R(D^*) = 0.270 \pm 0.035^{+0.028}_{-0.025}}$$

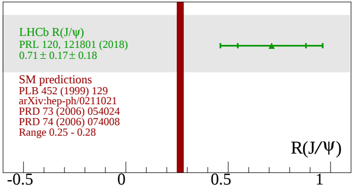
LHCb $R(D^*)$ 3-prong [PRL 120, 171802 (2018)] [PRL 120, 171802 (2018)]

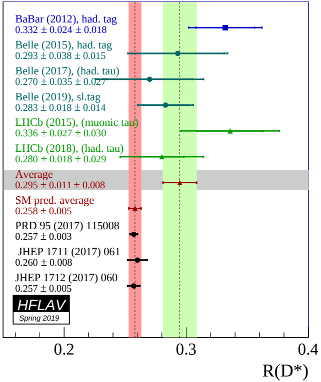
- Using $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$
- $\overline{B}^0 \to D^{*+} \tau^- \overline{\nu}_\tau$ yield from 3D template fit
  - $q^2 \equiv |P_{B^0} - P_{D^*}|^2$,
  - τ^+ decay time,
  - Output of BDT trained to kill $D^* D_s^+$.
- Normalise to $\overline{B}^0 \to D^{*+} 3\pi^\mp$
  - Yield from unbinned mass fit

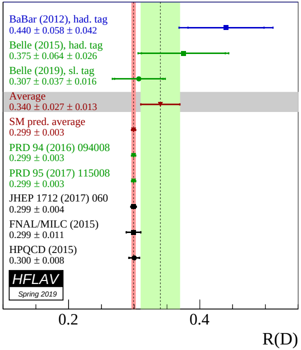


$$\boxed{R(D^*) = 0.291 \pm 0.019 \pm 0.026 \pm 0.013}$$

World averages





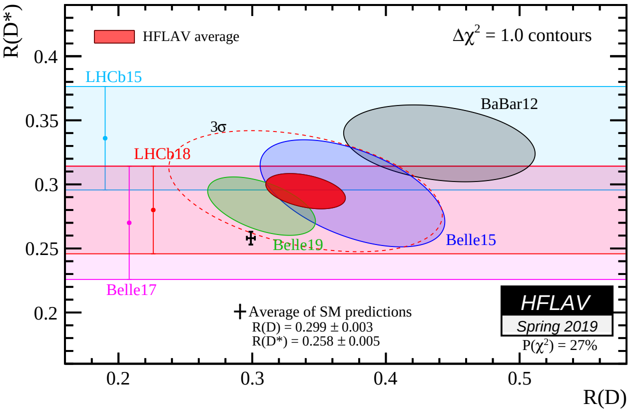


- $6 \times R(D^*)$, $3 \times R(D)$, $1 \times R(J/\psi)$.
- All central values lie above the SM expectation.

[HFLAV Spring 2019]

World averages

- HFLAV spring 2019 $R(D)$–$R(D^*)$ average is 3.1 σ from the SM.
- Reduction from 3.8 σ due to new Belle SL tag result, adding $R(D)$.



[HFLAV Spring 2019]

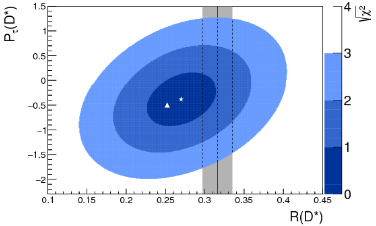
Angular measurements

From Belle $R(D^*)$ 1-prong analysis [PRL 118, 211801 (2017)] [PRD 97, 012004 (2018)]

- Fit split by different signs of τ helicity angle

$$P_\tau = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-}$$

- Result: $\boxed{P_\tau = -0.38 \pm 0.51^{+0.21}_{-0.16}}$
- Theory: $P_\tau = -0.497 \pm 0.013$ [PRD 87, 034028 (2013)], -0.488 ± 0.018 [arXiv:1908.09398]



$R(D^*)$–P_τ agrees with SM at 0.6σ

New (2019) result: Belle D^* polarisation in $B^0 \to D^{*-}\tau^+\nu_\tau$ [arXiv:1903.03102]

- Using $\tau^+ \to \ell^+\nu_\ell\overline{\nu}_\tau, \pi^+\overline{\nu}_\tau$
- Fit mass of $B_{\rm tag}$ simultaneously in 3 bins of $\cos\theta_D$

$$\frac{1}{\Gamma}\frac{d\Gamma}{\cos\theta_D} = \frac{3}{4}\left(2F_L\cos^2\theta_D + (1-F_L)\,sin^2\theta_D\right)$$

- Result: $\boxed{F_L = 0.60 \pm 0.08 \pm 0.04}$ $(1.6 \sim 1.8\sigma$ agreement)
- Theory: $F_L = 0.441 \pm 0.006$[PRD 98, 095018 (2018)], 0.457 ± 0.010[arXiv:1805.08222], 0.470 ± 0.012[arXiv:1908.09398]

Experimental prospects

- 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 depend on external measurements (BESIII, Belle II)
- LHCb plans: analyses of more modes
  - $b \to c\tau^-\overline{\nu}_\tau$: $R(D^+)$, $R(D^0)$, $R(D_s^{+(*)})$, $R(\Lambda_c^{+(*)})$ ...
  - $b \to u\tau^-\overline{\nu}_\tau$: $\Lambda_b^0 \to p\tau^-\overline{\nu}_\tau$, $B^+ \to p\overline{p}\tau^+\nu_\tau$ ...
- More angular observables!

Backup slides

Allowed NP scenarios and best-fit values of Wilson coefficients

Taken from a poster shown at EPS-HEP [link] which is an update to arXiv:1903.10486

Scenario	Best fit value(s)	χ^2_{min}	$P_\tau(D^*)$	$F_L(D^*)$	$A_{FB}(D^*)$	$\mathcal{B}\ (B_c^+ \to \tau^+\nu_\tau)$
SM	–	21.8	-0.499 ± 0.004	0.45 ± 0.04	-0.011 ± 0.007	2.15×10^{-2}
C_{V_L}	0.10 ± 0.02	4.5	-0.499 ± 0.004	0.46 ± 0.04	-0.011 ± 0.007	2.50×10^{-2}
C''_{S_L}	-0.34 ± 0.08	5.7	-0.493 ± 0.003	0.44 ± 0.05	-0.062 ± 0.010	1.14×10^{-6}
(C''_{S_L}, C''_{S_R})	$(0.27, 0.35)$	4.3	-0.494 ± 0.004	0.47 ± 0.04	$+0.027 \pm 0.008$	7.93×10^{-2}
(C_{V_R}, C_{S_L})	$(-0.14, 0.25)$	4.5	-0.526 ± 0.004	0.45 ± 0.04	-0.061 ± 0.006	2.15×10^{-3}
(C_{V_R}, C_{S_R})	$(-0.11, 0.22)$	3.9	-0.468 ± 0.004	0.47 ± 0.04	-0.023 ± 0.006	1.20×10^{-1}

- Belle II prospects: $F_L(D^*) \to \pm 0.04$ and $P_\tau(D^*) \to \pm 0.07$ [arXiv:1901.06380]
- Limit of $\mathcal{B}(B_c^+ \to \tau^+\nu_\tau) < 0.1$ from re-analysis of 40% of L3 Z^0-pole data, using later measurements of f_c/f_u and $\mathcal{B}\ (B^+ \to \tau^+\nu_\tau)$
  - Can be improved with (re-)analysis of full LEP-I data

Leptonic τ modes

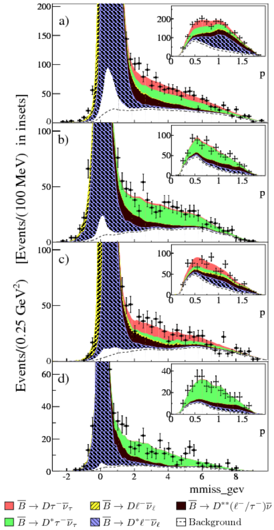
BaBar $R(D)$–$R(D^*)$ with hadronic tag

- 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)]

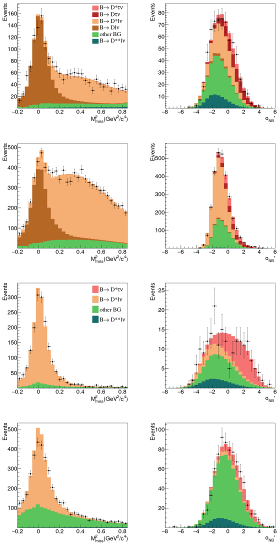
Belle $R(D)$–$R(D^*)$ with hadronic tag

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

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

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

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



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

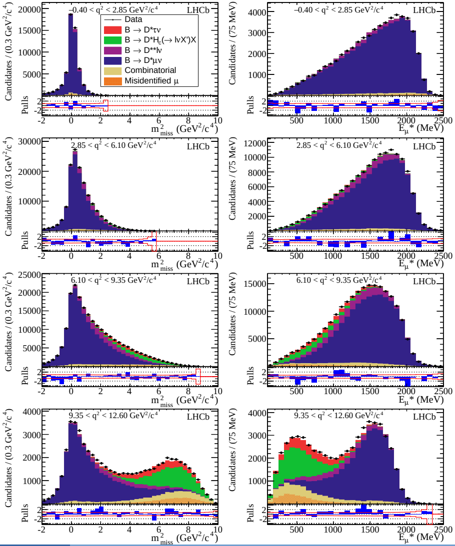
$$R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

- 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

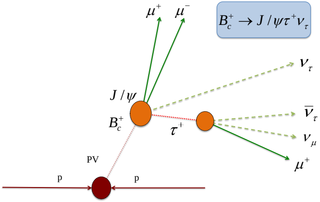
$$R(D^*) = 0.336 \pm 0.027\,(\mathrm{stat}) \pm 0.030\,(\mathrm{syst})$$

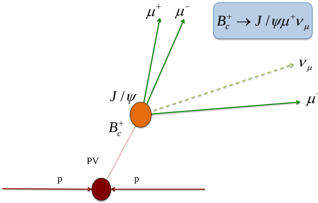
- 1.9 σ above SM
- Largest systematics: simulated sample size and mis-ID μ template



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

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





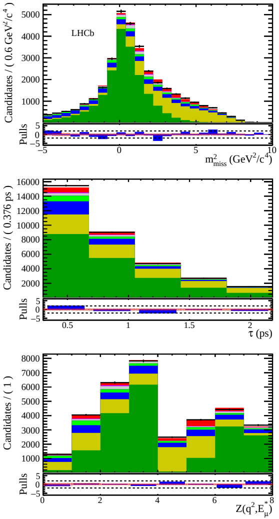
- Both modes have same visible final state: $J/\psi\, \mu^+$.
- 3D binned template fit to extract yields:
  - B_c^+ decay time,
  - m^2_{miss},
  - $Z(E^*_{\mu^+}, q^2) \equiv$ flattened 4×2 histogram of $E^*_{\mu^+}$, q^2.
- B_c^+ decay form factors not precisely determined; constrained experimentally 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).

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

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



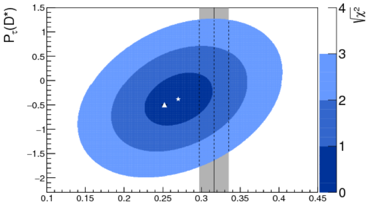
Hadronic τ modes

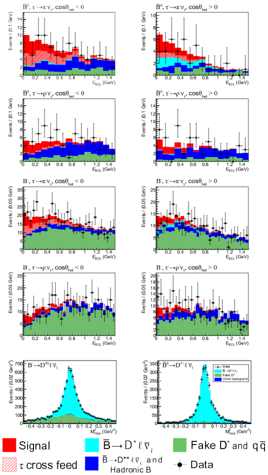
Belle $R(D^*)$ 1-prong hardonic and τ^- polarisation

- 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}

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

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





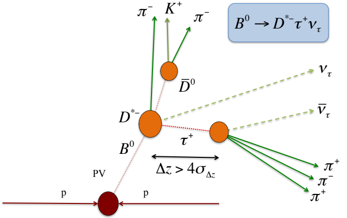
[PRD 97, 012004 (2018)]

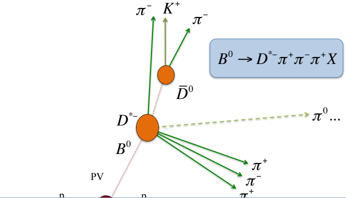
LHCb $R(D^*)$ 3-prong hadronic: introduction

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

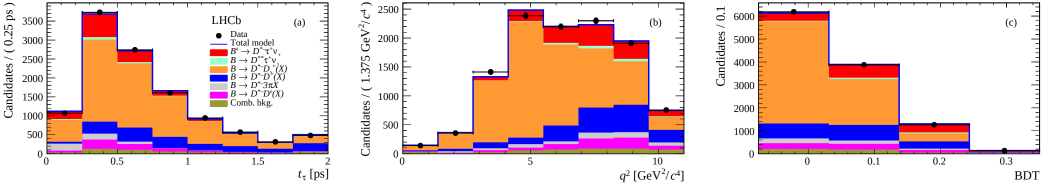
- Signal and normalisation same visible final state: $D^{*-}3\pi^\pm$.
- N_{sig} from 3D binned template fit:
  - $q^2 \equiv |P_{B^0} - P_{D^*}|^2$,
  - τ^+ decay time,
  - Output of BDT trained to kill $D^* D_s^+$.
- N_{norm} from unbinned max likelihood fit to $m(D^* 3\pi^\pm)$.
- Make use of three-prong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

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





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



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

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

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

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