Tests of Lepton Flavour Universality in semitauonic decays of b-hadrons at the LHCb experiment

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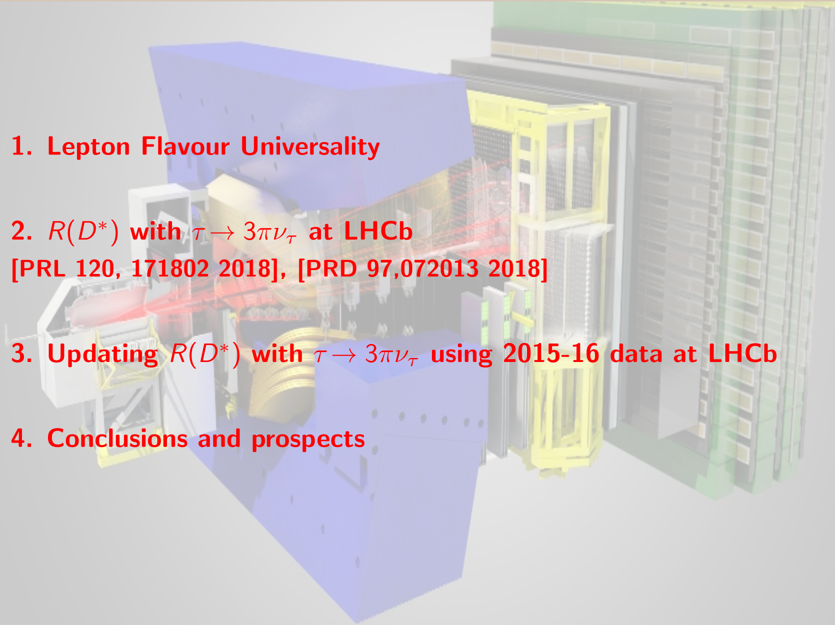
Outline



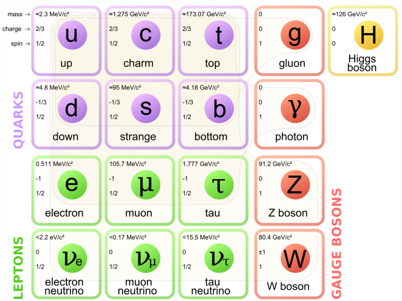
1. **Lepton Flavour Universality**

2. $R(D^*)$ **with** $\tau \to 3\pi\nu_\tau$ **at LHCb**
[PRL 120, 171802 2018], [PRD 97,072013 2018]

3. **Updating** $R(D^*)$ **with** $\tau \to 3\pi\nu_\tau$ **using 2015-16 data at LHCb**

4. **Conclusions and prospects**

Lepton Flavour Universality



- The Standard Model features

Lepton Flavour Universality (LFU): equal electroweak couplings to all charged leptons.

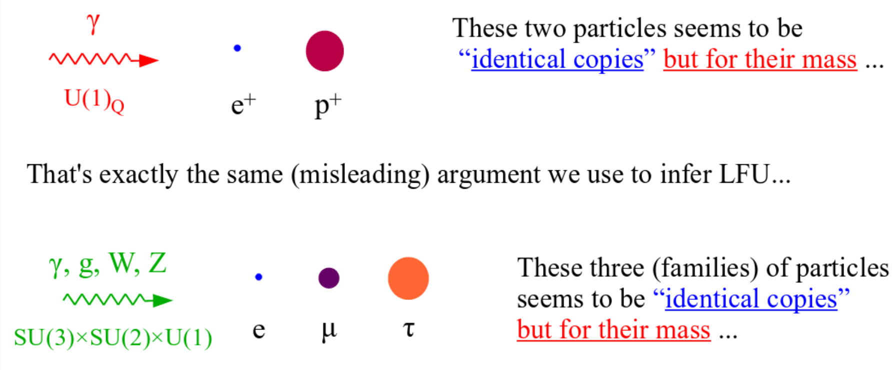
→ *Branching fractions* to e, μ and τ differ only due to their masses

- However, a deviation measured already at LEP:
  $\frac{2\sigma(W\to\tau\nu_\tau)}{\sigma(W\to e\nu_e)+\sigma(W\to\mu\nu_\mu)} = 1.077 \pm 0.026$, 2.8σ above SM

  [arXiv:0511027]

Inspiration for Lepton Flavour Non-Universality

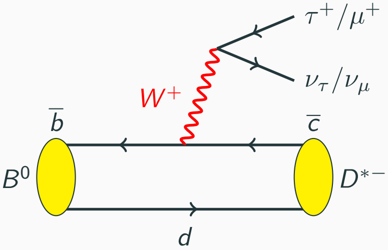
- Gino Isidori's talk at LHCb Implications Workshop (Nov '17):



Testing Lepton Flavour Universality at LHCb

The two probing modes:

- $b \rightarrow s\ell\ell$: *e.g.* $R(K^*)$
- $b \rightarrow c\ell\nu_\ell$: *e.g.* R($D^*$) – **this talk**



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

SM predictions:

$R(D^*)_{SM} = 0.258 \pm 0.005$

[HFLAV Summer 2018]

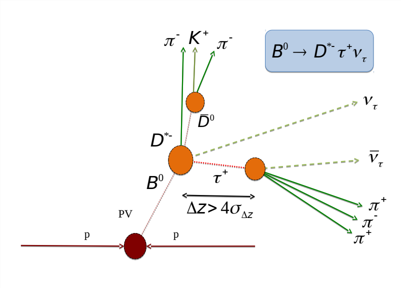
$R(D^*)$ with $\tau \to 3\pi\nu_\tau$ at LHCb

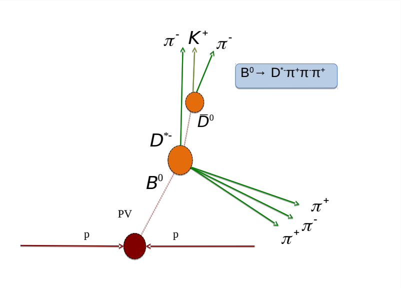
[PRL 120, 171802 2018], [PRD 97,072013 2018]

How do we measure $R(D^*)$?

Let's focus on $B^0 \to D^{*-}\tau^+\nu_\tau$

- proton-proton collider $\to$ a lot of background
- $\tau \to 3\pi\overline{\nu}_\tau$ ($\mathcal{B} \approx 14\%$) chosen $\to$ good τ vertex
- ν's present $\to$ partial reconstruction of signal
- heavily rely on simulation of all the modes
- Normalisation mode $B^0 \to D^*3\pi$ helps reduce uncertainties (full reco possible)

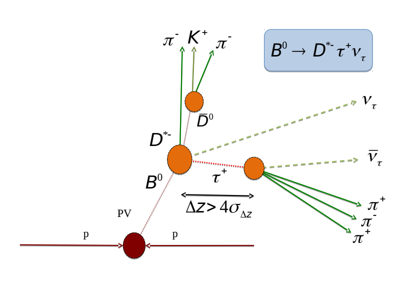


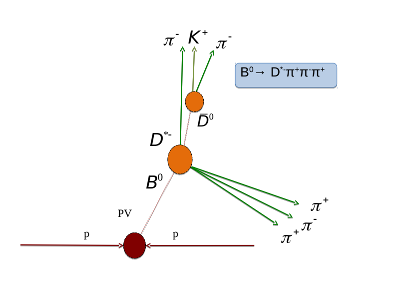


How do we measure $R(D^*)$?

$$R(D^*) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)} = \underbrace{\frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}}_{\equiv \mathcal{K}(D^*)} \times \frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$$

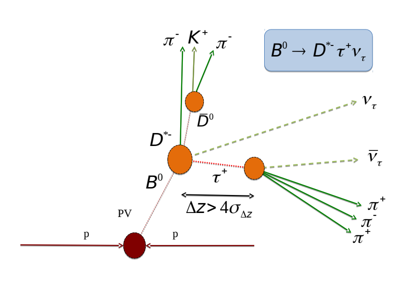
$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$	Known from BaBar with $\approx 2\%$ precision
$\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)$	BaBar, Belle and LHCb; $\approx 4\%$ precision
$\mathrm{K}(D^*)$	Measured by LHCb.

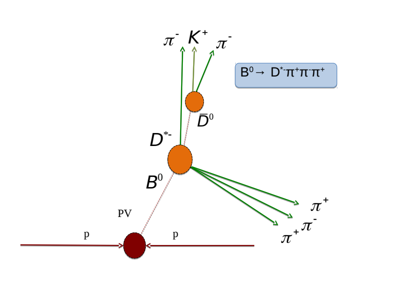




How do we measure $\mathcal{K}(D^*)$?

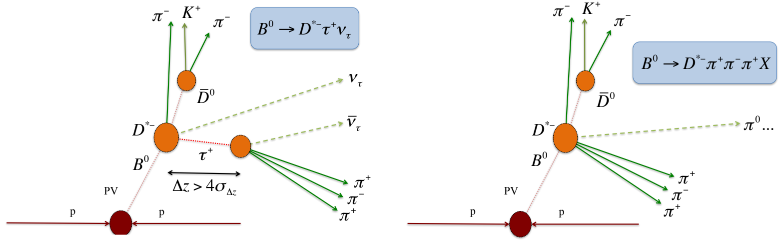
$$\mathcal{K}(D^*) \equiv \frac{N_{D^*\tau\nu_\tau}}{N_{D^*3\pi}} \times \frac{\varepsilon_{D^*3\pi}}{\varepsilon_{D^*\tau\nu_\tau}} \times \frac{1}{\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\overline{\nu}_\tau)}$$

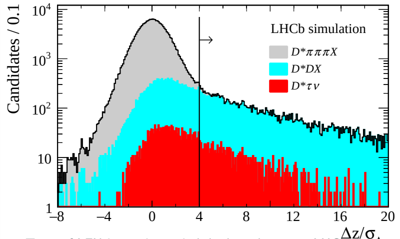




Main $R(D^*)$ backgrounds: $X_b \to D^{*-}3\pi X$

- 3π directly from the B^0
- $\mathcal{O}(100)$ larger than the signal



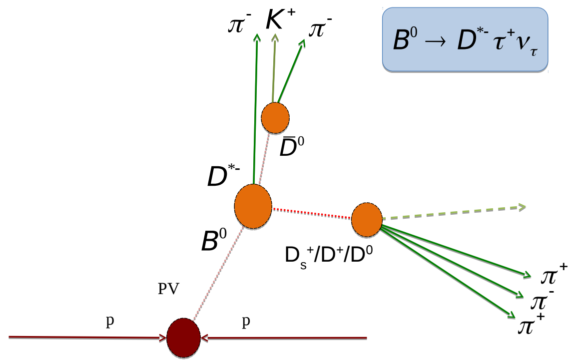


- **Vertex displacement** cut $\Delta z > 4\sigma_{\Delta z}$ improves S/B by 160
- Remaining background: $B \to D^* D(X)$ (double-charm decays)

Main $R(D^*)$ backgrounds: $X_b \to D^{*-} D(X)$

Challenge: D-mesons may live long enough to be mistaken for the τ

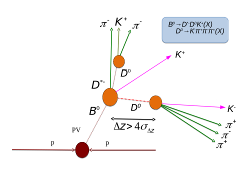
- $X_b \to D^{*-} D_s^+ X \sim 10\times$ signal
- $X_b \to D^{*-} D^+ X \sim 1\times$ signal
- $X_b \to D^{*-} D^0 X \sim 0.2\times$ signal

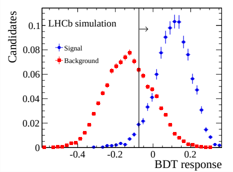


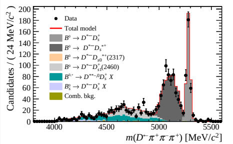
Main $R(D^*)$ backgrounds: $X_b \to D^{*-} D(X)$

The means to deal with these:

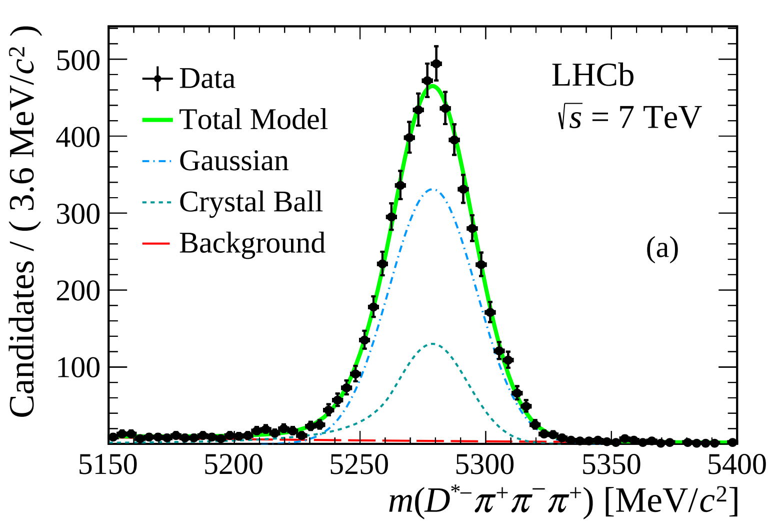
- Hunt down non-signal tracks forming "good" vertices with the signal-candidate tracks: **charged (neutral) isolation**
- impose Particle Identification (PID) requirements
- Exploit Multivariate Analysis: a Boosted Decision Trees used (kinematics, resonant structure, neutral isolation)
- Also use these techniques negatively: select bkgs to have a handle on them → validate & correct simulation







Normalisation yield



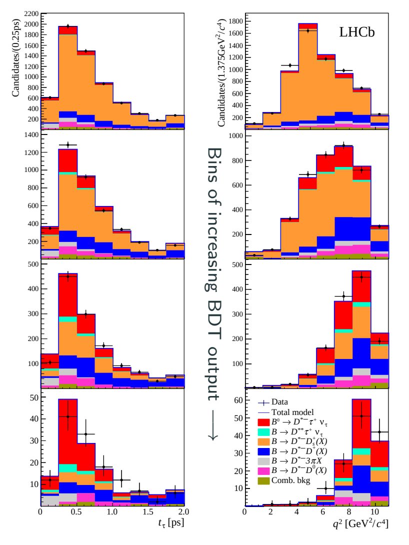
Obtained: $N_{norm} = 17660 \pm 143\,(\mathrm{stat}) \pm 64\,(\mathrm{syst}) \pm 22(sub)$ events

$R(D^*)$ final fit

- **3D template binned likelihood fit** results presented for the 3π **decay time** and $q^2 = (P_B - P_{D^*})^2$ in **4 BDT bins**
- Templates extracted from **simulation** and **data control samples**
- **Increase** in signal (red) purity as a function of BDT & **decrease** of the D_s^+ component (orange)
- Dominant background at high BDT: the D^+ component (blue), with its distinctive long lifetime
- $N(B^0 \to D^{*-}\tau^+\nu_\tau) = 1296 \pm 86$

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

0.9σ above SM



Updating $R(D^*)$ with $\tau \to 3\pi\nu_\tau$ using 2015-16 data at LHCb

The $R(D^*)$ 2011-12 bottleneck: systematics [PRL 120, 171802 2018]

- LHCb measured $R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$) using the 2011-12 data as:

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

- The goal of my analysis is to reduce the systematics: the highlighted contributions will be improved in my PhD:

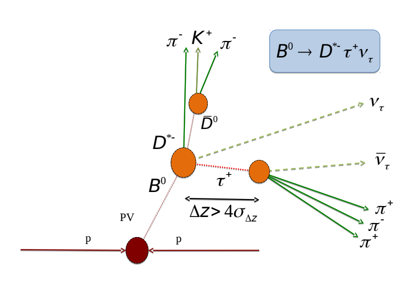
Source	$\frac{\delta R(D^{*-})}{R(D^{*-})}$ [%]	Future
Simulated sample size	4.7	Produce more MC !
Empty bins in templates	1.3	
Signal decay model	1.8	
$D^{**}\ \tau\ \ \nu$ and $D_s^{**}\ \tau\ \ \nu$ feed-downs	2.7	Measure $R(D^{**}(2420)^0)$
$D_s^+ \to 3\pi X$ decay model	2.5	BESIII
$B \to D^{*-}D_s^+X,\ D^{*-}D^+X,\ D^{*-}D^0X$ bkgs	3.9	Improves with stat
Combinatorial background	0.7	
$B \to D^{*-}3\pi X$ background	2.8	Kill with $\lvert z\tau - zD\rvert > 5\sigma$
Efficiency ratio	3.9	Improves with stat
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0	
Total systematic uncertainty	9.1	
Statistical uncertainty	6.5	
Total uncertainty	11.9	

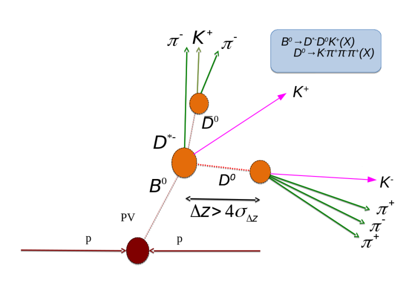
How to reduce the $R(D^*)$ uncertainties: 2015-16 vs. 2011-12

- **Statistics:** 2/3 integrated luminosity $\times$ 2 (cross-section due to 7-8 TeV $\rightarrow$ 13 TeV) $\times$ 1.15 trigger efficiency $\approx$ 1.5 more data
- **Systematics:** $\approx$ factor 4 more MC (w.r.t. data) $\rightarrow$ reduce systematics due to MC twice: need a few billion events! **need fast simulation**
- **External inputs:** measurements of D_s^+ decay model (*e.g.* BESIII measurements of $D_s^+ \rightarrow \pi^+\pi^0\eta$ and $D_s^+ \rightarrow \rho^+\eta$ shown at ICHEP 2018)

Improving charged track isolation

- **Charged track isolation:** no non-signal track forming a "good" vertex with a signal candidate track

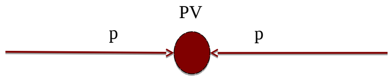




- 2011-12 analysis: cut-based
- My PhD: applied BDT based on geometry and kinematics of the tracks
  - Preliminary study (waiting for MC) shows signal efficiency increase from 70% to 80% and background (with extra charged tracks around 3π vertex) rejection increase from 90% to 95%
  - Meanwhile developing a data-driven BDT
  - Will choose the more performant of the two methods

Fast simulation with ReDecay – how it works?

- see poster [D. Müller and M. Rama],
- more info



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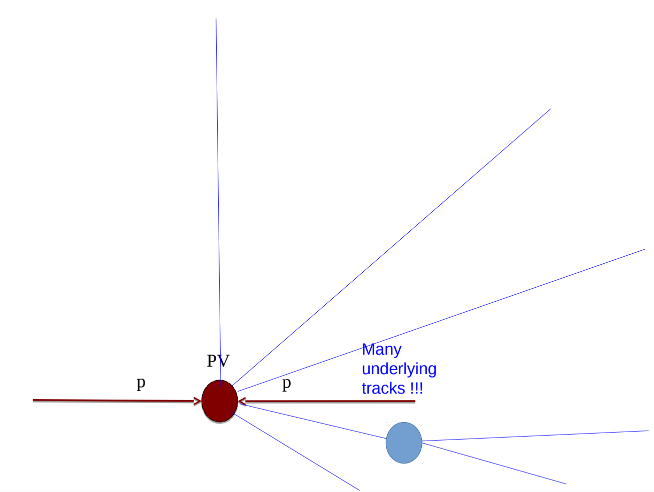

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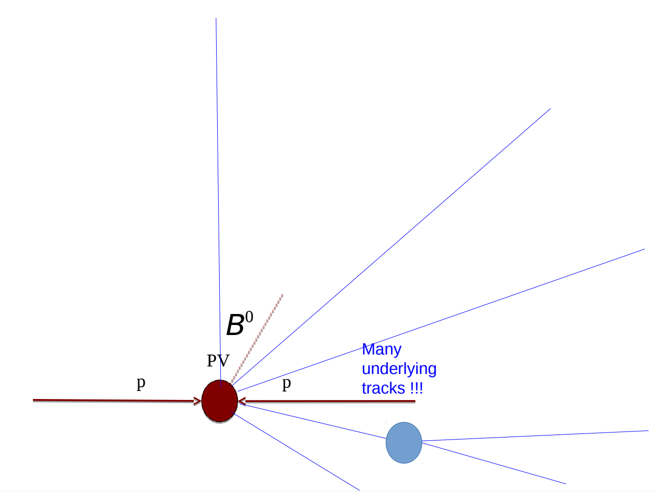

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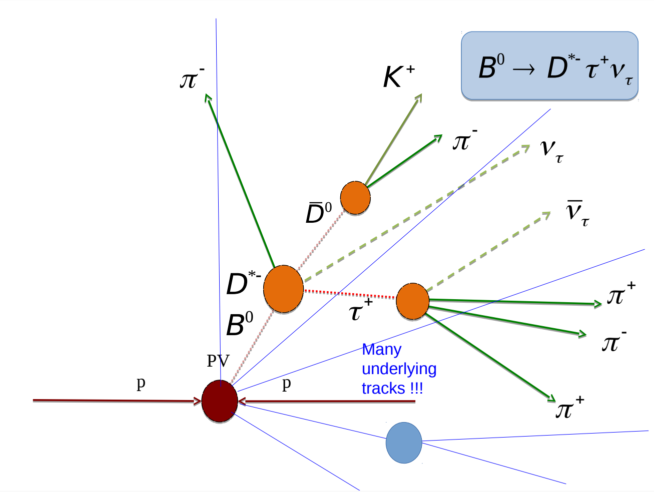

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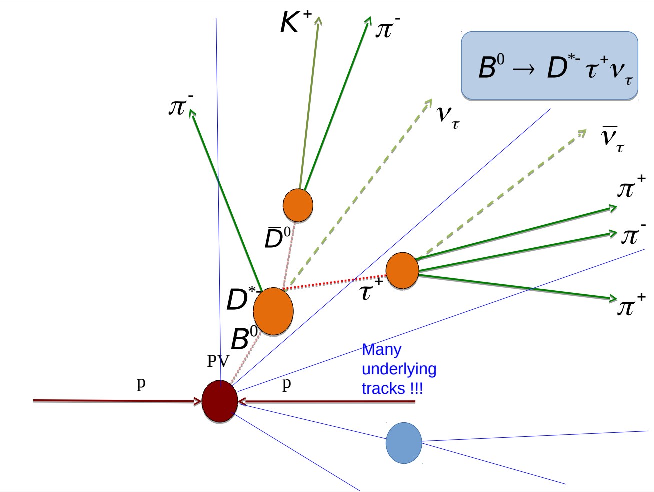
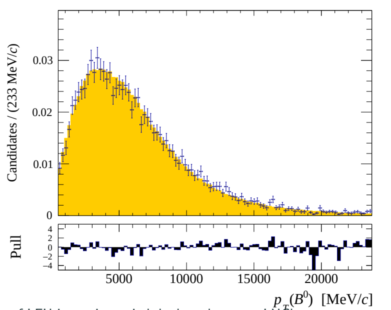
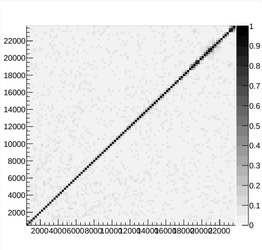


Validation of ReDecay for $R(D^*)$

- Produce $N_{blocks} \times N_{ReDecay} (= 100)$ events in a datasample
- 10-20 times faster, depending on mode
- Events in 1 block may be correlated $\rightarrow$ Poisson errors not applicable $\rightarrow$ block-bootstrapping: take n blocks with replacement $\rightarrow$ build histograms
- Agreement of full ("slow") simulation (orange) and fast simulation (ReDecay) for p_T of B^0 at the generator level for the signal

unofficial LHCb Simulation

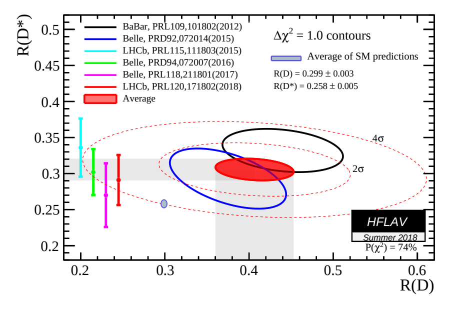




All $R(D)/R(D^*)$ measurements done so far

The ratios of these branching fractions probe LFU:

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

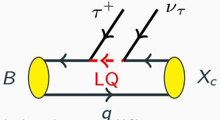


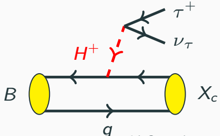
Combined $R(D^*)$ / $R(D)$ world-average from BaBar (2012), Belle (2015-16) and LHCb (2015/17) shows **3.8σ tension with the Standard Model!**

Conclusions and prospects

Conclusions and prospects

- **Exciting times**: interesting deviations suggesting Lepton Flavour Non-Universality observed in $R(D)/\ R(D^*)$ and $R(J/\Psi)$, 3.8σ and $\approx 2\sigma$ away from SM
- In the next few years **more results to come** (LHCb & Belle2)
- The LHCb Run2 data (2015–18) currently under investigation hoping to significantly decrease the uncertainties
- Constantly trying to improve the analysis techniques w.r.t. Run1: fast simulation, cleaner selection (isolation), anti-$DD(X)$ Multivariate Analysis, *etc.*
- Theoreticians are feverly cooking up various New Physics models. Do leptoquarks exist?





Backup

Treatment of statistical errors in ReDecay

Adapted from D. Müller's thesis (CERN-THESIS-2017-257)
Bootstrapping:

- Start with a sample of size n
- Make a pseudo-sample of n' random entries from the original sample
  - n' is drawn randomly from a Poisson distribution with mean n
- Non-independence of ReDecay events requires sampling whole 'blocks'
- Make many pseudo-samples and bin in histograms
- Take the mean n_i^{bs} and standard deviation σ_i^{bs} of each bin i across all histograms j to form the the bootstrapped distribution

$$n_i^{\text{bs}} = \frac{1}{N}\sum_j^N n_i^j; \qquad \sigma_i^{\text{bs}} = \sqrt{\frac{1}{N}\sum_j^N \left(n_i^j - n_i^{\text{bs}}\right)^2}$$

$$\text{corr}_{k,l}^{\text{bs}} = \frac{1}{\sigma_k^{\text{bs}}\sigma_l^{\text{bs}}}\frac{1}{N}\sum_j^N \left(n_k^j - n_k^{\text{bs}}\right)\left(n_l^j - n_l^{\text{bs}}\right)$$

More Monte Carlo → fast simulation

To address this "need for speed" there exist following solutions:

- **Simplified detector** (as Geant4 takes up 95-99% of CPU time), e.g. $R(D^*)$ muonic removed the RICH'es.
- **Parametrisation**, e.g. **Delphes**: replacing the Geant4 with parametrisation (Benedetto Siddi).
- **Shower libraries** of hits in ECAL and HCAL.
- **ReDecay**: redecaying given "mother" particles multiple times from the same pp collision → reducing CPU time by a factor of 10-15.

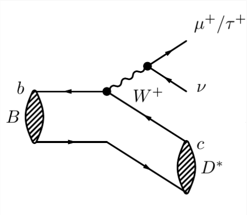
Only ReDecay is available immediately.

Note, other solutions are complementary and may be added once ready.

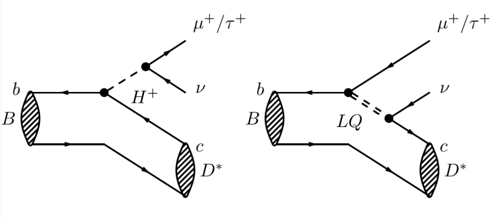
Possible New Physics contributions

- If LFU is violated then the Standard Model (SM) picture of decays involving leptons will have to be enriched.
- In particular, assuming $R(D)$ / $R(D^*)$ discrepancy persist, the decays
  $B^0 \to D^{*-}\ \tau^+\nu_\tau$ and $B^0 \to D^{*-}\ \mu^+\nu_\mu$ will have to be complemented.
- The New Physics (NP) possible contributions include hypothetical charged Higgs bosons or Leptoquarks.

SM diagram



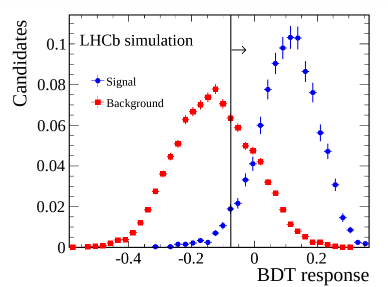
NP candidates: charged Higgs and Leptoquarks



Main $R(D^*)$ backgrounds: $X_b \to D^{*-} D_s^+ (X)$

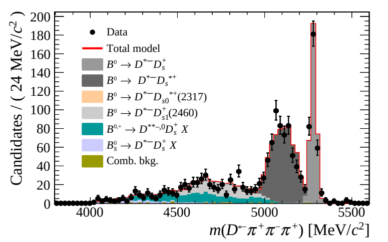
Rejected with a **Boosted Decision Tree** using

- the **resonant structures** of the $\tau^+ \to 3\pi\bar{\nu}_\nu$ and $D_s^+ \to 3\pi X$ decays
- **energy of neutral particles** around the 3π vertex deposited in the calorimeter
- **kinematics**



Different $X_b \to D^{*-} D_s^+ X$ contributions determined from $D_s^+ \to 3\pi$ decays (simulation + data).

Clear separation between D_s, D_s^* and D_s^{**}



Fit to data for candidates containing a D^{*-} D_s^+ pair, where $D_s^+ \to 3\pi$.

Tantalizing tensions with respect to the SM

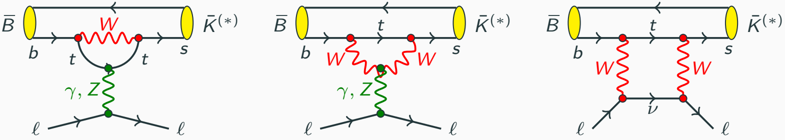
Observable	Tension wrt SM	Limited by
$B \to D^{(*)}\tau\nu / B \to D^{(*)}\ell\nu,\ \ell = \mu, e$	3.8σ	experiment
$(g-2)_\mu$	3.6σ	exp. & theo.
$B^0 \to K^{*0}\mu\mu$ angular dist., BR	3.4σ	exp. & theo.
$B_s^0 \to \phi\mu\mu$ BR	3.0σ	experiment
$2\sigma(W \to \tau\nu_\tau)/(\sigma(W \to e\nu_e) + \sigma(W \to \mu\nu_\mu))$	2.8σ	experiment
$B^+ \to K^+\mu\mu / B^+ \to K^+ee$	2.6σ	experiment
$B^0 \to K^{*0}\mu\mu / B^0 \to K^{*0}ee$	2.6σ	experiment
$B_c^+ \to J/\psi\,\tau^+\nu / B_c^+ \to J/\psi\,\mu^+\nu$	2.0σ	exp. & theo.

Many other interesting results exhibit no tension today, but put strong constraints on NP models.

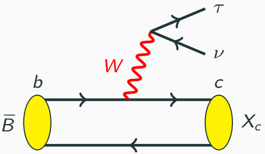
They remain fundamental for future searches, e.g.: γ, B^0-D^0-K^0-mixing, ϕ_s, $\sin 2\beta$, $B_s^0 \to \mu\mu$, $B \to X_s\gamma$, V_{cb}, $B \to \tau\nu$, CPV in charm, CLVF, $K \to \pi\nu\bar{\nu}$, ...

Flavor Anomalies

- $b \to s\ell\ell$



- $b \to c\tau\nu_\tau$



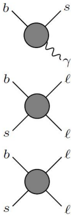
Effective field theory

Transition $B \to f$ described by an effective Hamiltonian $\langle f|\mathcal{H}_{\rm eff}|B\rangle$, with

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{tq}^* \sum_i (\underbrace{C_i \mathcal{O}_i}_{\rm Left-handed} + \underbrace{C_i' \mathcal{O}_i'}_{\rm Right-handed})$$

Computed by splitting into:

- C_i (Wilson coefficients): short distance (perturbative) effective couplings, can be computed in terms of fundamental couplings of the SM and beyond
- $\langle f|\mathcal{O}_i|B\rangle$: long distance (non perturbative), computed using QCD at low energy or extracted by phenomenological analysis. $\mathcal{O}_i$ are local operators:



	$b \to s\gamma$	$B \to \mu\mu$	$b \to s\ell\ell$
$\mathcal{O}_7^{(\prime)}$ photon penguin	✓		✓
$\mathcal{O}_9^{(\prime)}$ vector coupling			✓
$\mathcal{O}_{10}^{(\prime)}$ axialvector coupling		✓	✓
$\mathcal{O}_{S,P}^{(\prime)}$ (pseudo)scalar penguin		✓	

Fundamental parameters of the Standard Model

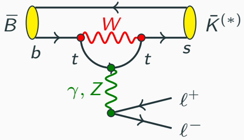
The 28 parameters of the Standard Model are:

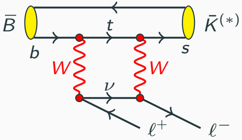
- the 3 coupling constant associated to $SU(2)_L \times U(1)_Y$ and $SU(3)_c$,
- the 2 Higgs field potential parameters μ and λ,
- the six quark masses and the six lepton masses,
- the four CKM parameters
- the six MNS parameters
- the possible QCD CP violating phase θ_{QCD}.

Two front LFU tests

- $R(K^{(*)}) = \mathcal{B}(B \to K^{(*)}\mu^+\mu^-)/\mathcal{B}(B \to K^{(*)}e^+e^-)$

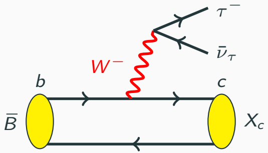
- **FCNC $b \to s\ell\ell$**
- Rare decay forbidden at the tree level
- Very sensitive to NP contributions in the loops





- $R(X_c) = \mathcal{B}(B \to X_c\tau^+\nu_\tau)/\mathcal{B}(B \to X_c\mu^+\nu_\mu), \quad X_c = D,\ D^*$ or J/ψ

- **Tree level $\rightarrow c\tau\nu_\tau$**
- Abundant semileptonic decay
- Very well known in SM
- Possible NP coupling mainly to the 3rd family



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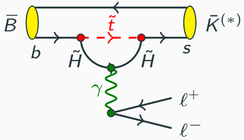

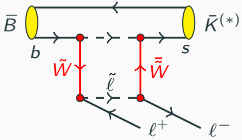

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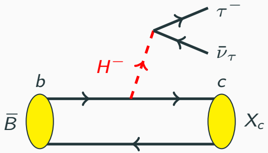


Lepton Flavor Universality in semileptonic decays

While semileptonic μ/e ratios are tested at 5% level by Belle:

$R(D)(\mu/e) = 0.995 \pm 0.022(\mathrm{stat}) \pm 0.039(\mathrm{syst})$ [Belle, PRD 93, 032006 (2016)]

$R(D^*)(\mu/e) = 0.96 \pm 0.05(\mathrm{stat}) \pm 0.01(\mathrm{syst})$ [Belle, 1702.01521]

we observe a $\sim$18% enhancement from the SM in the τ/μ ratio.

$B \to (\to D\pi)\ell_\ell$: observables sensitive to NP

[D. Bečirević, S. Fajfer, I. Nišandžić, A. Tayduganov, arXiv:1602.03030]

What can be extracted from the proposed observables:

$d\Gamma/dq^2$	$\left[\lvert H_+\rvert^2 + \lvert H_-\rvert^2 + \lvert H_0\rvert^2\right]\left(1+\frac{m_\ell^2}{2q^2}\right) + \frac{3}{2}\frac{m_\ell^2}{q^2}\lvert H_t\rvert^2$	
$1-\mathcal{A}_{\lambda_\ell}$	$\lvert H_+\rvert^2 + \lvert H_-\rvert^2 + \lvert H_0\rvert^2 + 3\lvert H_t\rvert^2$	
$\mathcal{A}_{\rm FB}$	$\lvert H_+\rvert^2 - \lvert H_-\rvert^2 + 2\frac{m_\ell^2}{q^2}\Re\left[H_0 H_t^*\right]$	
$R_{L,T}$	$\lvert H_+\rvert^2 + \lvert H_-\rvert^2$	
A_5	$\lvert H_+\rvert^2 - \lvert H_-\rvert^2$	
C_χ	$\Re\left[H_+ H_-^*\right]$	
S_χ	$\Im\left[H_+ H_-^*\right]$	(=0 in the SM)
A_8	$\Im\left[(H_+ + H_-)H_0^* - \frac{m_\ell^2}{q^2}(H_+ - H_-)H_t^*\right]$	(=0 in the SM)
A_9	$\Re\left[(H_+ - H_-)H_0^* - \frac{m_\ell^2}{q^2}(H_+ + H_-)H_t^*\right]$	
A_{10}	$\Im\left[(H_+ - H_-)H_0^*\right]$	(=0 in the SM)
A_{11}	$\Re\left[(H_+ + H_-)H_0^*\right]$	

Best discriminating variable to NP

$$Heff = \frac{G_F}{\sqrt{2}} V_{cb} \big[(1 + g_V) \gamma_\mu b + (-1 + g_A) \gamma_\mu \gamma_5 b + g_S \, i\partial_\mu (b) + g_P \, i\partial_\mu (\gamma_5 b) + g_T \, i\partial_\nu (i\sigma_{\mu\nu} b) \big] (\gamma^\mu (1 - \gamma_5) \nu_\ell)$$

[D. Bečirević, S. Fajfer, I. Nišandžić, A. Tayduganov, arXiv:1602.03030]

$\times$: "not sensitive"

$\star\star\star$: "maximally sensitive"

Quantity	g_V	g_A	g_S	g_P	g_T
$\mathcal{A}_{\rm FB}^{D}$	$\times$	$-$	$\star\star\star$	$-$	$\star$
$\mathcal{A}_{\lambda_\tau}^{D}$	$\times$	$-$	$\star\star\star$	$-$	$\star\star$
$\mathcal{A}_{\rm FB}^{D^*}$	$\star$	$\star\star\star$	$-$	$\star\star\star$	$\star$
$\mathcal{A}_{\lambda_\tau}^{D^*}$	$\times$	$\times$	$-$	$\star\star$	$\star$
$R_{L,T}$	$\times$	$\times$	$-$	$\star\star$	$\star\star$
A_5	$\star\star$	$\star\star$	$-$	$\star$	$\star\star\star$
C_χ	$\star$	$\times$	$-$	$\star\star$	$\star\star$
S_χ	$\star\star\star$	$\star\star\star$	$-$	$\times$	$\star\star\star$
A_8	$\star\star$	$\star\star$	$-$	$\star\star$	$\star\star\star$
A_9	$\star$	$\star$	$-$	$\star\star$	$\star\star$
A_{10}	$\star\star$	$\star\star$	$-$	$\times$	$\star\star$

SM expectation for $R(D^*)$ [[S.Fajfer et al., PRD 85(2012) 094025]

$$\frac{d\Gamma_\ell}{dq^2} = \frac{G_F^2\,|V_{cb}|^2\,|\mathbf{p}|q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2 \times \left[\left(|H_{++}|^2+|H_{--}|^2+|H_{00}|^2\right)\left(1+\frac{m_\ell^2}{2q^2}\right)+\frac{3m_\ell^2}{2q^2}|H_{0t}|^2\right],$$

$q^2 = (p_B - p_{D^*})^2$ and $\mathbf{p}$ is the 3-mom of the D^* meson in the B rest frame:

$$|\mathbf{p}| = \frac{\sqrt{\lambda(m_B^2, m_{D^*}^2, q^2)}}{2m_B},\ \lambda(a,b,c) = a^2+b^2+c^2-2(ab+bc+ca).$$

H_{mn} are the hadronic helicity amplitudes:

$$\begin{aligned}
H_{\pm\pm}(q^2) =& (m_B+m_{D^*})A_1(q^2) \mp \frac{2m_B}{m_B+m_{D^*}}|\mathbf{p}|V(q^2),\\
H_{00}(q^2) =& \frac{1}{2m_{D^*}\sqrt{q^2}} \times \left[(m_B^2-m_{D^*}^2-q^2)(m_B+m_{D^*})A_1(q^2) - \frac{4m_B^2|\mathbf{p}|^2}{m_B+m_{D^*}}A_2(q^2)\right],\\
H_{0t}(q^2) =& \frac{2m_B|\mathbf{p}|}{\sqrt{q^2}}A_0(q^2),
\end{aligned}$$

$A_{0,1,2}(q^2)$, $V(q^2)$ are the the form factors.

SM expectation for $R(D^*)$ [[S.Fajfer et al., PRD 85(2012) 094025]

To calculate these form factors it is useful to define the kinematical variable:

$$w = v_B \cdot v_{D*} = \frac{m_B^2 + m_{D*}^2 - q^2}{2m_B m_{D*}},$$

v_B, v_{D*} are the four-velocities of B and D^*. It is possible to define $A_{0,1,2}(q^2)$, $V(q^2)$ in terms of four variables $h_{A_1}(w), R_{0,1,2}(w)$:

$$A_1(q^2) = h_{A_1}(w)\frac{1}{2}(w+1)R, \quad (2a)$$

$$A_0(q^2) = \frac{R_0(w)}{R}h_{A_1}(w), \quad (2b)$$

$$A_2(q^2) = \frac{R_2(w)}{R}h_{A_1}(w), \quad (2c)$$

$$V(q^2) = \frac{R_1(w)}{R}h_{A_1}(w), \quad (2d)$$

where $R = 2\sqrt{m_B m_{D*}}/(m_B + m_{D*})$. According to the HQET computation of [CLN 1998], the w dependence of these quantities is given by:

$$h_{A_1}(w) = h_{A_1}(1)[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3], \quad (3a)$$

$$R_0(w) = R_0(1) - 0.11(w-1) + 0.01(w-1)^2, \quad (3b)$$

$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2, \quad (3c)$$

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2, \quad (3d)$$

with $z = (\sqrt{w+1} - \sqrt{2})/(\sqrt{w+1} + \sqrt{2})$.

SM expectation for $R(D^*)$ [[S.Fajfer et al., PRD 85(2012) 094025]

$$R_{D^*}(q^2) = \frac{d\Gamma_\tau/dq^2}{d\Gamma_\ell/dq^2} =$$

$$= \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left[\left(1 + \frac{m_\tau^2}{2q^2}\right) + \frac{3m_\tau^2}{2q^2} \frac{|H_{0t}|^2}{|H_{++}|^2 + |H_{--}|^2 + |H_{00}|^2}\right]$$

where $d\Gamma_\ell/dq^2$ has been calculated in an analogous way to $d\Gamma_\tau/dq^2$.

Integrating over q^2 gives $R(D^*)$.

Citing HFLAV: New calculations are available since the 2017. The most relevant input to these new calculations are: form factors obtained fitting with the [BGL 1995] parameterization the unfolded spectrum from Belle [arXiv:1702.01521]. These new calculations are in good agreement between each other, and consistent with the old predictions for $R(D^*)$, but more robust. There are differences in the evaluation of the theoretical uncertainty associated mainly to assumptions on the pseudoscalar Form Factor. The central values of the SM predictions, and their uncertainty estimates, will evolve as more precise measurements of $B \to D^* \ell\nu$ spectra are available and new calculations are available. The disagreement on the treatment of the theoretical uncertaitines can be settled down when calculation of the $B \to D^*$ Form Factors beyond the zero recoil limit as well as information on the pseudoscalar Form Factor will be available.

	$R(D)$	$R(D^*)$
D.Bigi, P.Gambino, Phys.Rev. D94 (2016) no.9, 094008 [arXiv:1606.08030 [hep-ex]]	0.299 ± 0.003	
F.Bernlochner, Z.Ligeti, M.Papucci, D.Robinson, Phys.Rev. D95 (2017) no.11, 115008 [arXiv:1703.05330 [hep-ex]	0.299 ± 0.003	$0.257 \pm$
D.Bigi, P.Gambino, S.Schacht, JHEP 1711 (2017) 061 [arXiv:1707.09509 [hep-ex]]		$0.260 \pm$
S.Jaiswal, S.Nandi, S.K.Patra, JHEP 1712 (2017) 060 [arXiv:1707.09977 [hep-ex]]	0.299 ± 0.004	$0.257 \pm$
Arithmetic average	$\mathbf{0.299 \pm 0.003}$	$\mathbf{0.258 \pm}$

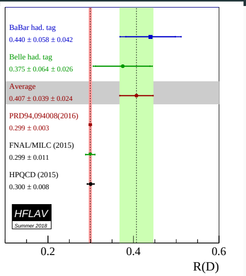
$R(D^*)$ and $R(D)$ summary

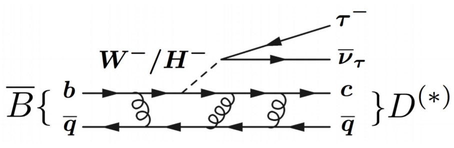
- Similarly to $R(D^*)$, the ratio is defined for D^- mesons:

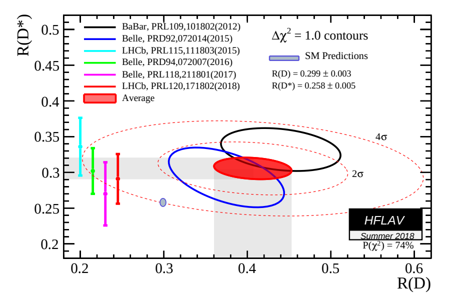
$$R(D) = \frac{\mathcal{B}(B^0 \to D^- \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^- \ell^+ \nu_\ell)}$$

and has been measured by Belle and BaBar

- Theoretical predictions: $R(D) = 0.299 \pm 0.003$







- Combination of LHCb, Belle and BaBar: **3.8σ wrt SM!**

Properties of charged leptons

Particle	Mass (MeV/c^2)	Lifetime	Main decay modes
e^-	0.5109989461(31)	¿6.6×10^{26} years	None
μ^-	105.6583745(24)	2.1969811(22) μs	$e^-\bar{\nu}_e\nu_\mu$
τ^-	1776.86(12)	290.3(5) fs	$\pi^-\pi^0\nu_\tau$ (25.5%) $e^-\bar{\nu}_e\nu_\tau$ (17.8%) $\mu^-\bar{\nu}_\mu\nu_\tau$ (17.39%) $\pi^-\nu_\tau$ (10.8%) $\pi^-\pi^+\pi^-\nu_\tau$ (9.3%)

D^* branching ratios

Mode	BR
$D^*(2007)^0 \to D^0\pi^0$	$(64.7 \pm 0.9)\%$
$D^*(2007)^0 \to D^0\gamma$	$(35.3 \pm 0.9)\%$
$D^*(2010)^+ \to D^0\pi^+$	$(67.7 \pm 0.5)\%$
$D^*(2010)^+ \to D^+\pi^0$	$(30.7 \pm 0.5)\%$
$D^*(2010)^+ \to D^+\gamma$	$(1.6 \pm 0.4)\%$

Particle	Mass (MeV/c^2)	Lifetime
D^+	1869.65 ± 0.05	(1.040 ± 0.007) ps
D^0	1864.83 ± 0.05	(0.4101 ± 0.0015) ps
D_s^+	1968.34 ± 0.07	(0.504 ± 0.004) ps
Λ_c^+	2286.46 ± 0.14	(0.200 ± 0.006) ps
$D^*(2007)^0$	2006.85 ± 0.05	-
$D^*(2010)^-$	2010.26 ± 26	-

τ lepton Branching Ratios [PDG 2018]

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

$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$)

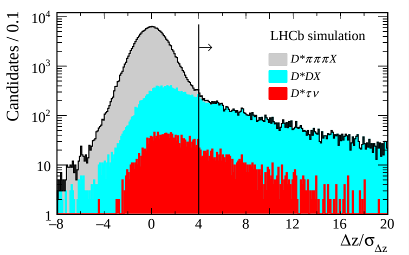
$R(D^*)$ **hadronic** $(\tau \to 3\pi\nu_\tau)$ [PRD 97,072013 2018]

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

with $$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)} = \frac{N_{D^*\tau\nu_\tau}}{N_{D^*3\pi}} \times \frac{\varepsilon_{D^*3\pi}}{\varepsilon_{D^*\tau\nu_\tau}} \times \frac{1}{\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\bar{\nu}_\tau)}$$

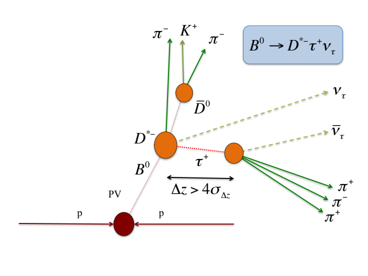
- Signal and normalization modes chosen to have the same final state
- $\mathcal{B}(\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau) = (9.31 \pm 0.05)\%$
- $\mathcal{B}(\tau^+ \to \pi^+\pi^-\pi^+\pi^0\bar{\nu}_\tau) = (4.62 \pm 0.05)\%$
- $N_{D^*3\pi}$ from unbinned fit to $D^*3\pi$ invariant mass
- $N_{D^*\tau\nu_\tau}$ from binned templated fit
- $\mathcal{B}(B^0 \to D^{*-}3\pi)$ from [BaBar, PRD94 (2016) 091101] ($\sim$4% precision)
- $\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$ from PDG ($\sim$2% precision)

$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$) [PRD 97,072013 2018]

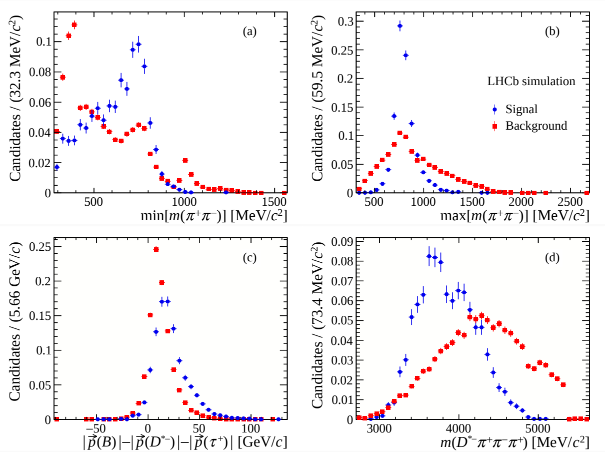


Distribution of the distance between the B^0 vertex and the 3π vertex along the beam direction, divided by its uncertainty, obtained using simulation. The grey area corresponds to the prompt background component, the cyan and red areas to double-charm and signal components, respectively. The vertical line shows the 4σ requirement used in the analysis to reject the prompt background component

$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$) [PRL 120, 171802 2018], [PRD 97,072013 2018]

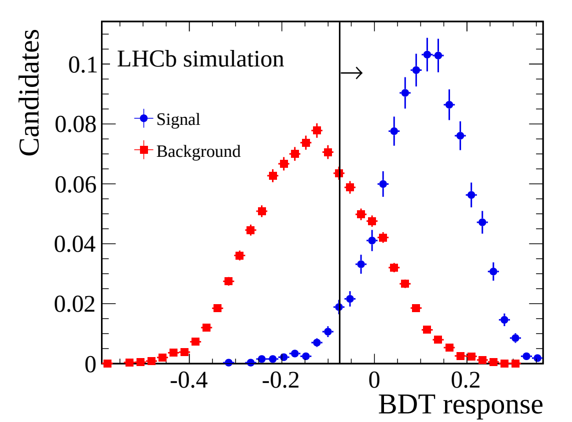


$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$). Anti-D_s^+ BDT [PRD 97,072013 2018]



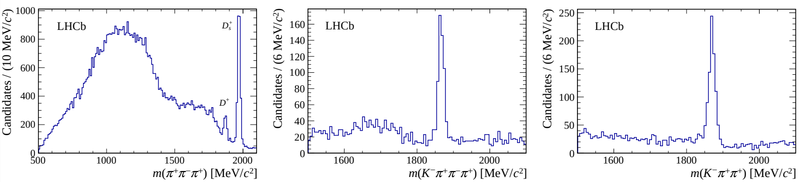
Normalized distributions of (a) min[$m(\pi^+\pi^-)$], (b) max[$m(\pi^+\pi^-)$], (c) approximated neutrino momentum reconstructed in the signal hypothesis, and (d) the $D^{*-}3\pi$ mass in simulated samples.

$R(D^*)$ **hadronic** $(\tau \to 3\pi\nu_\tau)$ [PRD 97,072013 2018]



Distribution of the BDT response on the signal and background simulated samples.

$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$)
D_s^+, D^0 and D^+ control channels [PRD 97,072013 2018]

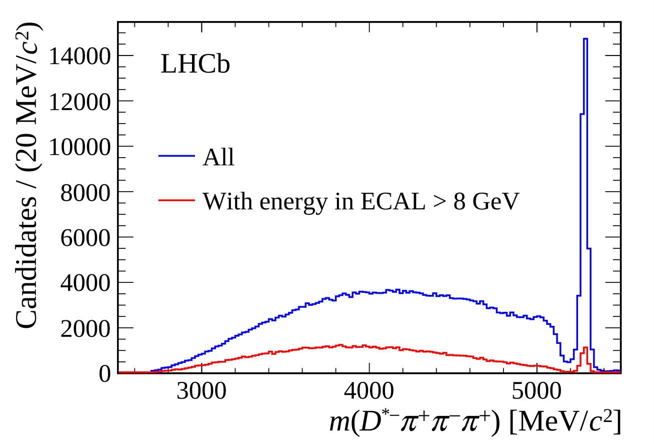


Left: Distribution of the 3π mass for candidates after the detached-vertex requirement. The D^+ and D_s^+ mass peaks are indicated.

Center: Distribution of the $K^-3\pi$ mass for D^0 candidates where a charged kaon has been associated to the 3π vertex. (anti-isolation)

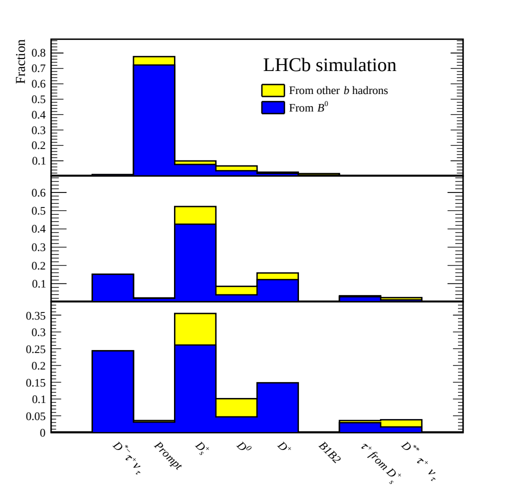
Right: Distribution of the $K^-\pi^+\pi^+$ mass for D^+ candidates passing the signal selection, where the negative pion has been identified as a kaon and assigned the kaon mass. (antiPID)

$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$). Neutral Isolation [PRD 97,072013 2018]



Distribution of the $D^{*-}3\pi$ mass (blue) before and (red) after a requirement of finding an energy of at least $8\,\mathrm{GeV}$ in the electromagnetic calorimeter around the 3π direction.

$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$) [PRD 97,072013 2018]



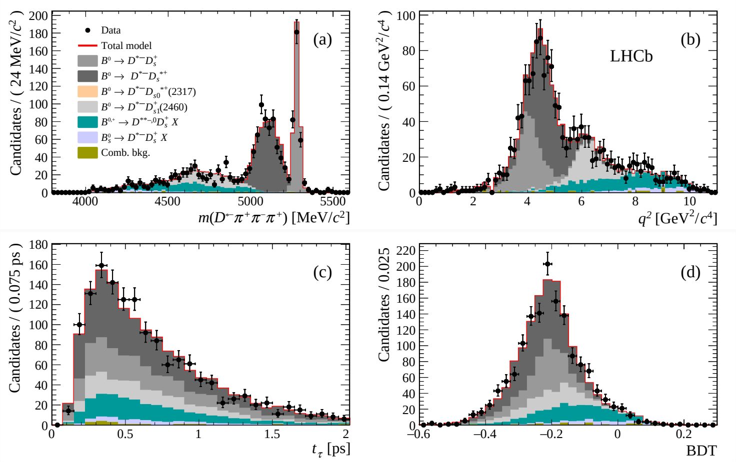
Composition of an inclusive simulated sample where a D^{*-} and a 3π system have been produced in the decay chain of a $b\bar{b}$ pair from a pp collision. Each bin shows the fractional contribution of the different possible parents of the 3π system (blue from a B^0, yellow for other b hadrons): from signal; directly from the b hadron (prompt); from a charm parent D_s^+, D^0, or D^+ meson; 3π from a B and the D^0 from the other B ($B1B2$); from τ lepton following a D_s^+ decay; from a τ lepton following a $D^{**}\tau^+\nu_\tau$ decay (D^{**} denotes here any higher excitation of D mesons).

(Top) After the initial selection and the removal of spurious 3π candidates.

(Middle) For candidates entering the signal fit.

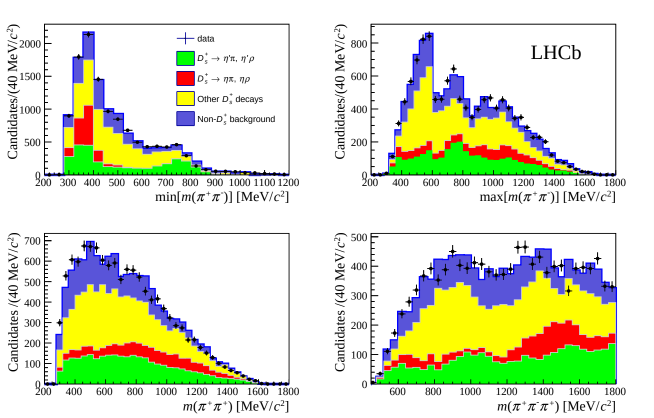
(Bottom) For candidates populating the last 3 bins of the BDT distribution.

$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$) Control Sample [PRD 97,072013 2018]



Results from the fit to data for candidates containing a D^{*-} D_s^+ pair, where $D_s^+ \to 3\pi$. The figures correspond to the fit projection on (a) $m(D^{*-}3\pi)$, (b) q^2, (c) 3π decaytime t_τ and(d) BDT output distributions.

$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$). D_s^+ decay model [PRD 97,072013 2018]



The 4 distributions are fitted simultaneously with a fit model obtained from MC. Sample enriched in $B \to D^{*-} D_s^+(X)$ decays, obtained by requiring the BDT output below a certain threshold.

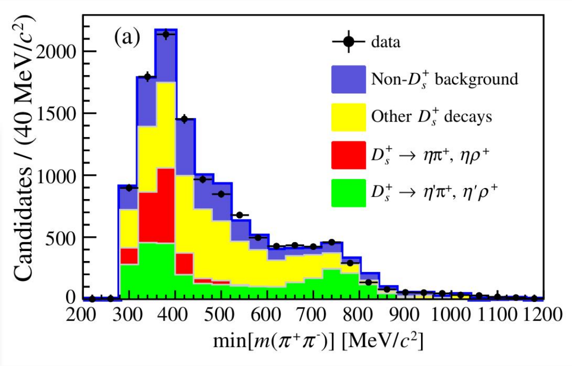
D_s^+ decays with at least 1 pion from η (red) or η' (green): $\eta^{(\prime)}\pi^+$, $\eta^{(\prime)}\rho^+$

D_s^+ decays with at least 1 pion from an intermediate state (IS) other than η or η': ω or ϕ (yellow)

D_s^+ decays where none of the 3 pions come from an IS, backgrounds originating from decays not involving the D_s^+ meson:

$K^0 3\pi$, $\eta 3\pi$, $\eta' 3\pi$, $\omega 3\pi$, $\phi 3\pi$, non-resonnnt (blue).

$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$). D_s^+ decay model [PRD 97,072013 2018]



The τ lepton decays through the $a_1(1260)^+$ resonance, which leads to the $\rho^0\pi^+$ final. The dominant source of ρ^0 resonances in D_s^+ decays is due to $\eta' \to \rho^0\gamma$ decays. It is therefore crucial to control the η' contribution in D_s^+ decays very accurately.

At low min[$m(\pi^+\pi^-)$], only η and η' (red, green) contributions are peaking: $\eta \to \pi^+\pi^-\pi^0$ and $\eta' \to \eta\pi^+\pi^-$. At the ρ^0 mass where the signal lives, only η' contributes: $\eta' \to \rho^0\gamma$. The shape of this η' contribution is precisely known since the η' branching fractions are known to better than 2%. The precise measurement on data of the low-mass excess, which consists only of η' and η candidates, therefore enables the control of the η' contribution in the sensitive ρ region.

Fits results used to describe the $D_s^+ \to 3\pi X$ model in the final fit for $N_{\rm sig}$

$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$). D_s^+ decay model [PRD 97,072013 2018]

Results of the fit to the D_s^+ decay model. The relative contribution of each decay and the correction to be applied to the simulation are reported in the second and third columns, respectively.

D_s^+ decay	Relative contribution	Correction to simulation
$\eta\pi^+(X)$	0.156 ± 0.010	
$\eta\rho^+$	0.109 ± 0.016	0.88 ± 0.13
$\eta\pi^+$	0.047 ± 0.014	0.75 ± 0.23
$\eta'\pi^+(X)$	0.317 ± 0.015	
$\eta'\rho^+$	0.179 ± 0.016	0.710 ± 0.063
$\eta'\pi^+$	0.138 ± 0.015	0.808 ± 0.088
$\phi\pi^+(X)$, $\omega\pi^+(X)$	0.206 ± 0.02	
$\phi\rho^+$, $\omega\rho^+$	0.043 ± 0.022	0.28 ± 0.14
$\phi\pi^+$, $\omega\pi^+$	0.163 ± 0.021	1.588 ± 0.208
$\eta 3\pi$	0.104 ± 0.021	1.81 ± 0.36
$\eta' 3\pi$	0.0835 ± 0.0102	5.39 ± 0.66
$\omega 3\pi$	0.0415 ± 0.0122	5.19 ± 1.53
$K^0 3\pi$	0.0204 ± 0.0139	1.0 ± 0.7
$\phi 3\pi$	0.0141	0.97
$\tau^+(\to 3\pi(N)\overline{\nu}_\tau)\nu_\tau$	0.0135	0.97
$X_{\rm nr} 3\pi$	0.038 ± 0.005	6.69 ± 0.94

$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$) [PRD 97,072013 2018]

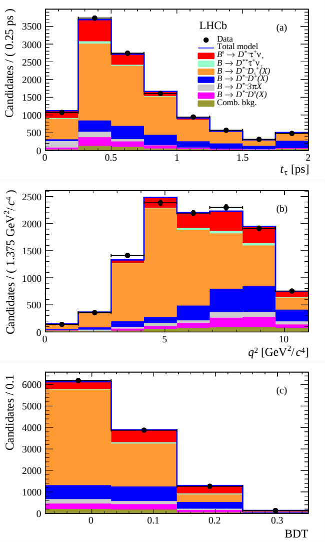
Projections of the three-dimensional fit on the

(a) 3π decay time

(b) q^2 and

(c) BDT output

distributions.



$R(D^*)$ **hadronic** $(\tau \to 3\pi\nu_\tau)$ [PRD 97,072013 2018]

Summary of fit components and their corresponding normalization parameters. The first three components correspond to parameters related to the signal.

Fit component	Normalization
$B^0 \to D^{*-}\tau^+(\to 3\pi\overline{\nu}_\tau)\nu_\tau$	$N_{\rm sig} \times f_{\tau\to 3\pi\nu}$
$B^0 \to D^{*-}\tau^+(\to 3\pi\pi^0\overline{\nu}_\tau)\nu_\tau$	$N_{\rm sig} \times (1 - f_{\tau\to 3\pi\nu})$
$B \to D^{**}\tau^+\nu_\tau$	$N_{\rm sig} \times f_{D^{**}\tau\nu}$
$B \to D^{*-}D^+X$	$f_{D^+} \times N_{D_s}$
$B \to D^{*-}D^0X$ different vertices	$f_{D^0}^{v_1v_2} \times N_{D^0}^{\rm sv}$
$B \to D^{*-}D^0X$ same vertex	$N_{D^0}^{\rm sv}$
$B^0 \to D^{*-}D_s^+$	$N_{D_s} \times f_{D_s^+}/k$
$B^0 \to D^{*-}D_s^{*+}$	$N_{D_s} \times 1/k$
$B^0 \to D^{*-}D_{s0}^*(2317)^+$	$N_{D_s} \times f_{D_{s0}^{*+}}/k$
$B^0 \to D^{*-}D_{s1}(2460)^+$	$N_{D_s} \times f_{D_{s1}^+}/k$
$B^{0,+} \to D^{**}D_s^+X$	$N_{D_s} \times f_{D_s^+X}/k$
$B_s^0 \to D^{*-}D_s^+X$	$N_{D_s} \times f_{(D_s^+X)_s}/k$
$B \to D^{*-}3\pi X$	$N_{B\to D^*3\pi X}$
B1B2 combinatorics	N_{B1B2}
Combinatoric D^{*-}	$N_{{\rm not}D^*}$

$R(D^*)$ **hadronic** $(\tau \to 3\pi\nu_\tau)$ [PRD 97,072013 2018]

Fit results for the three-dimensional fit. The constraints on the parameters $f_{D_s^+}$, $f_{D_{s0}^{*+}}$, $f_{D_{s1}^+}$, $f_{D_s^+X}$ and $f_{(D_s^+X)_s}$ are applied taking into account their correlations.

Parameter	Fit result	Constraint
$N_{\rm sig}$	1296 ± 86	
$f_{\tau\to 3\pi\nu}$	0.78	0.78 (fixed)
$f_{D^{**}\tau\nu}$	0.11	0.11 (fixed)
$N_{D^0}^{\rm sv}$	445 ± 22	445 ± 22
$f_{D^0}^{v_1 v_2}$	0.41 ± 0.22	
N_{D_s}	6835 ± 166	
f_{D^+}	0.245 ± 0.020	
$N_{B\to D^* 3\pi X}$	424 ± 21	443 ± 22
$f_{D_s^+}$	0.494 ± 0.028	0.467 ± 0.032
$f_{D_{s0}^{*+}}$	$0^{+0.010}_{-0.000}$	$0^{+0.042}_{-0.000}$
$f_{D_{s1}^+}$	0.384 ± 0.044	0.444 ± 0.064
$f_{D_s^+X}$	0.836 ± 0.077	0.647 ± 0.107
$f_{(D_s^+X)_s}$	0.159 ± 0.034	0.138 ± 0.040
N_{B1B2}	197	197 (fixed)
$N_{{\rm not}D^*}$	243	243 (fixed)

$R(D^*)$ hadronic $(\tau \to 3\pi\nu_\tau)$ [PRD 97,072013 2018]

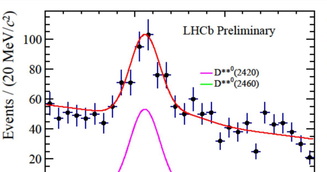
$$R(D^*) = 0.291 \pm 0.019(\mathrm{stat}) \pm 0.026(\mathrm{syst}) \pm 0.013(\mathrm{ext})$$

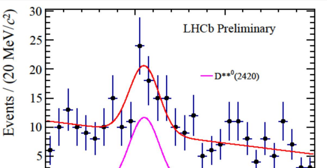
List of the individual systematic uncertainties for $R(D^*)$:

Contribution	Value in %
$\mathcal{B}(\tau^+ \to 3\pi\overline{\nu}_\tau)/\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\overline{\nu}_\tau)$	0.7
Form factors (template shapes)	0.7
Form factors (efficiency)	1.0
τ polarization effects	0.4
Other τ decays	1.0
$B \to D^{**}\tau^+\nu_\tau$	2.3
$B_s^0 \to D_s^{**}\tau^+\nu_\tau$ feed-down	1.5
$D_s^+ \to 3\pi X$ decay model	2.5
D_s^+, D^0 and D^+ template shape	2.9
$B \to D^{*-}D_s^+(X)$ and $B \to D^{*-}D^0(X)$ decay model	2.6
$D^{*-}3\pi X$ from B decays	2.8
Combinatorial background (shape + normalization)	0.7
Bias due to empty bins in templates	1.3
Size of simulation samples	4.1
Trigger acceptance	1.2
Trigger efficiency	1.0
Online selection	2.0
Offline selection	2.0
Charged-isolation algorithm	1.0
Particle identification	1.3
Normalization channel	1.0
Signal efficiencies (size of simulation samples)	1.7
Normalization channel efficiency (size of simulation samples)	1.6
Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)	2.0

$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$) D^{**} [PRD 97,072013 2018]

- $B^0 \to D^{**}\tau\nu$ and $B^+ \to D^{**}\tau\nu$ constitute potential feed-down to the signal
- $D^{**}(2420)^0$ is reconstructed using its decay to $D^{*+}\pi^+$ **as a cross-check**
- The observation of the $D^{**}(2420)^0$ peal allow to compute the $D^{**}3\pi$ BDT distribution and to deduce a $D^{**}\tau\nu$ upper limit with the following assumption:
    - $D^{**0}\tau\nu = D^{**}(2420)^0\tau\nu$ (no sign of $D^{**}(2460)^0$)
    - $D^{**+}\tau\nu = D^{**0}\tau\nu$
- This upper limit is consistent with the theoretical prediction
- Subtraction in the signal of 0.11 ± 0.04 due to $D^{**}\tau\nu$ events leading to an error of 2.3%





$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$) Systematics [PRL 120, 171802 2018]

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

Breakdown of relative uncertainties:

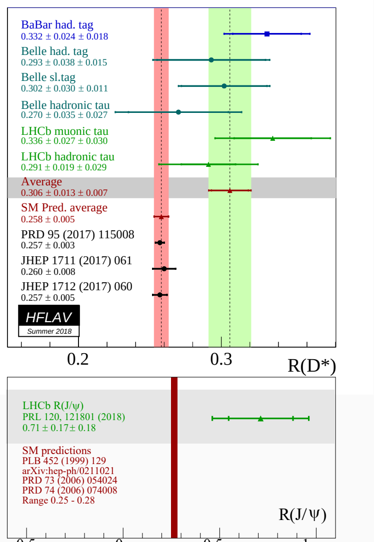
Source	$\frac{\delta R(D^{*-})}{R(D^{*-})}$ [%]	Future
Simulated sample size	4.7	Produce more MC !
Empty bins in templates	1.3	
Signal decay model	1.8	
$D^{**}\ \tau\ \ \nu$ and $D_s^{**}\ \tau\ \ \nu$ feed-downs	2.7	Measure $R(D^{**}(2420)^0)$
$D_s^+ \to 3\pi X$ decay model	2.5	BESIII
$B \to D^{*-} D_s^+ X,\ D^{*-} D^+ X,\ D^{*-} D^0 X$ bkgs	3.9	Improves with stat
Combinatorial background	0.7	
$B \to D^{*-} 3\pi X$ background	2.8	Kill with $\|z\tau - zD\| > 5\sigma$
Efficiency ratio	3.9	Improves with stat
Normalization channel efficiency (modeling of $B^0 \to D^{*-} 3\pi$)	2.0	
Total systematic uncertainty	9.1	
Statistical uncertainty	6.5	
Total uncertainty	11.9	

$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$) Improvement of systematics in the future [PRL 120, 171802 2018]

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

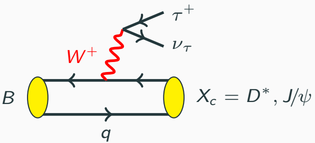
- Shape of $B \to D^* DX$ background (2.9%): scale with statistics
- $D_s^+ \to 3\pi X$ decay model (2.5%): BESIII future measurement will help to significantly reduce this uncertainty.
- Branching fraction of normalisation mode $B^0 \to D^* 3\pi$ can be precisely measured by Belle II.
- $B \to D^{*-} 3\pi X$ background can be easily removed by a strong cut on the distance significance between the τ and the D^0 vertices.
- With more stat, measure $R(D^{**}(2420)^0)$ and constraint D^{**} feed-down
- Efficiency ratio: will improve with more stat.

$R(D^*)$ and $R(J/\psi)$ summary



3 experiments, 7 measurements, different analysis techniques: ALL $R(D^*)$ and $R(J/\psi)$ measurements lie ABOVE the SM expectations.

$R(D^*)$ average 3.0σ above the SM prediction [HFLAV]



Possible NP contributions ?