Tests of Lepton Flavour Universality using semitauonic decays at LHCb

Dawid Gerstel, Olivier Leroy, Adam Morris and $R(D^*)$ Run1 proponents

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The GDR-InF annual workshop, Arles, 5-7 Nov ’18

Outline

1. **Introduction**

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**

Introduction

What is Lepton Flavour Universality?

- The Standard Model features

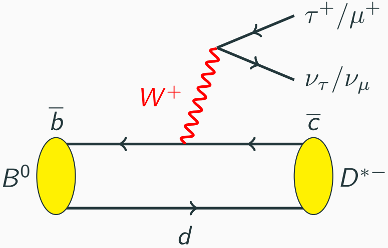
Lepton Flavour Universality (LFU): equal electroweak couplings to all charged leptons.

$\rightarrow$ *Branching fractions* to e, μ and τ differ only due to their masses

- However, a deviation measured already at LEP:
  $\frac{2\sigma(W\rightarrow\tau\nu_\tau)}{\sigma(W\rightarrow e\nu_e)+\sigma(W\rightarrow\mu\nu_\mu)} = 1.077 \pm 0.026$, 2.8σ above SM
  [https://doi.org/10.1016/j.physrep.2013.07.004]
- Some BSM models predict enhanced coupling to the 3rd generation (*e.g.* Leptoquarks) $\rightarrow$ LFU violation

Testing Lepton Flavour Universality at LHCb

this talk: $b \to c\ell\nu_\ell$: *e.g.* $\mathrm{R}(D^*)$



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

SM predictions:

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

[HFLAV Summer 2018]

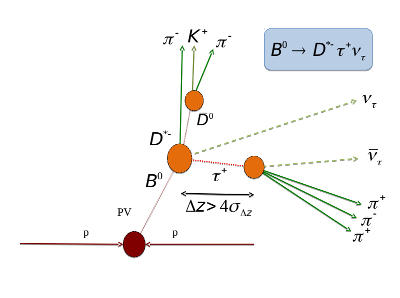
$R(D^*)$ with $\tau \to 3\pi\nu_\tau$ at LHCb

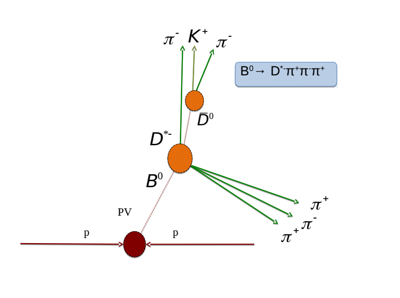
[PRL 120, 171802 2018], [PRD 97,072013 2018]

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

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

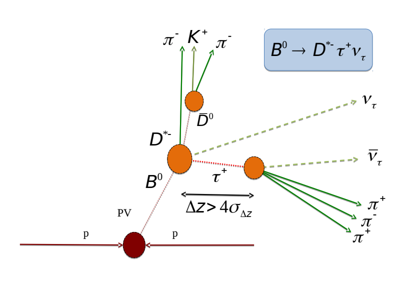
$\mathcal{K}(D^*)$	Measured by LHCb.
$\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^-\pi^+)$	BaBar, Belle and LHCb; $\approx$ 4% precision
$\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)$	Known from BaBar with $\approx$ 2% precision

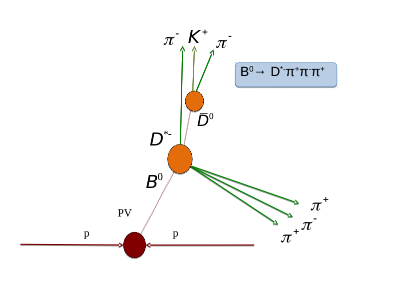




How do we measure $\mathcal{K}(D^*)$?

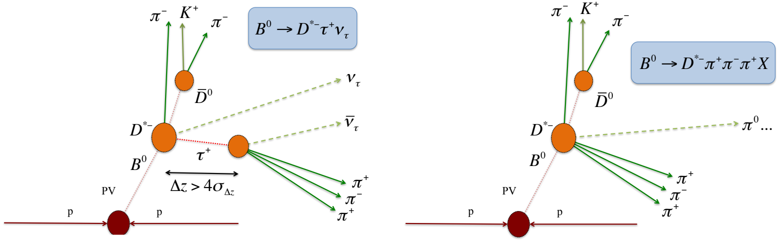
$$\mathcal{K}(D^*) \equiv \frac{N_{D^*\tau\nu_\tau}}{N_{D^*3\pi}} \times \frac{\varepsilon_{D^*3\pi}}{\varepsilon_{D^*\tau\nu_\tau}} \times \frac{1}{\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\overline{\nu}_\tau)}$$

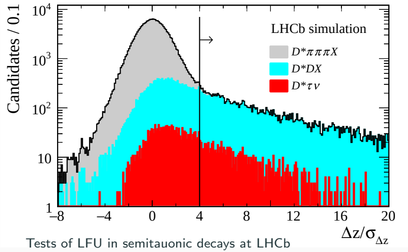




$R(D^*)$ backgrounds (1/2): $X_b \to D^{*-} 3\pi X$

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

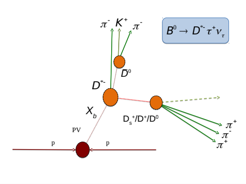


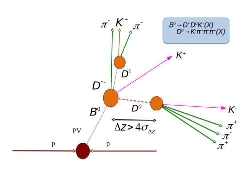


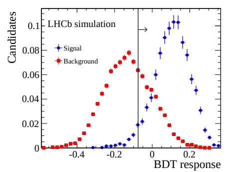
- **Vertex displacement** cut $\Delta z > 4\sigma_{\Delta z}$ improves S/B by 160
- Remaining background: $B \to D^* D(X)$ (double-charm decays)

$R(D^*)$ backgrounds (2/2): $X_b \to D^{*-}D(X)$

- **charged (neutral) isolation:** Hunt down non-signal tracks forming "good" vertices with the signal-candidate tracks:
- 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





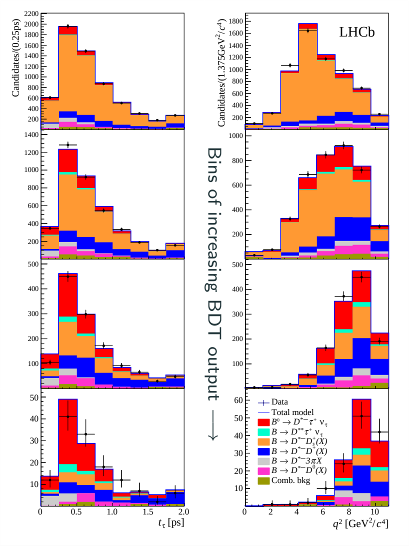


$R(D^*)$ final fit

- **3D template binned likelihood fit:** 3π decay time, $q^2 = (P_B - P_{D^*})^2$ and BDT
- 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

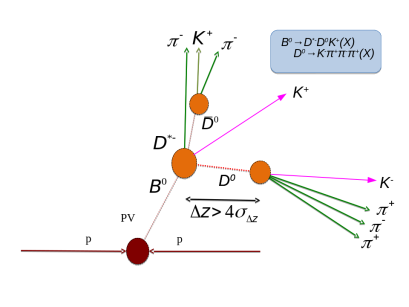
$$R(D^*) = 0.291 \pm 0.019(\text{stat}) \pm \mathbf{0.026}(\text{syst}) \pm 0.013(\text{ext})$$

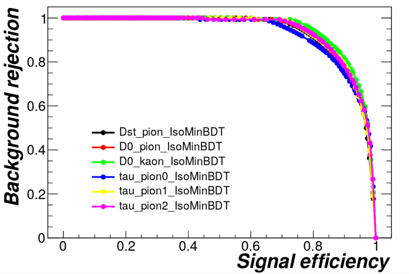
- The goal of my analysis is to **reduce the systematics**: the highlighted contributions will be improved in my PhD:

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 $\|z\tau - zD\| > 5\sigma$
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	

Improving charged track isolation

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

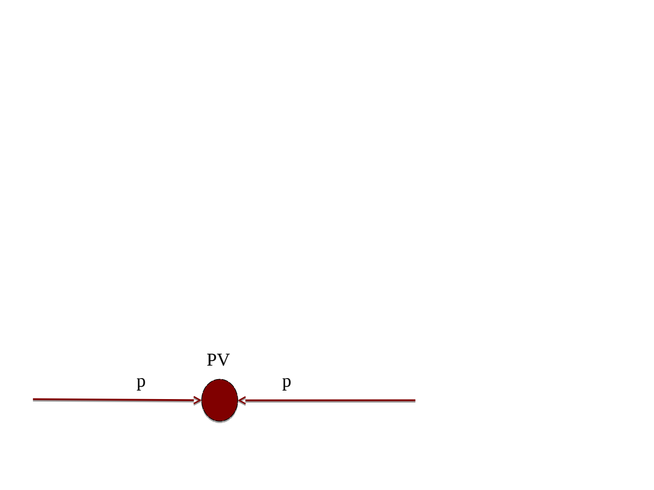




- 2011-12 analysis: cut-based
- My PhD: applied BDT based on geometry and kinematics of the tracks
    - Preliminary study (waiting for MC) shows **signal efficiency increase from 70% to 80%** and **background rejection increase from 90% to 95%**
    - Meanwhile developing a data-driven BDT

Fast simulation with ReDecay – how it works?

"ReDecay: A novel approach to speed up the simulation at LHCb"
D. Müller *et al.* → Submitted to Eur. Phys. J. C arXiv:1810.10362v1



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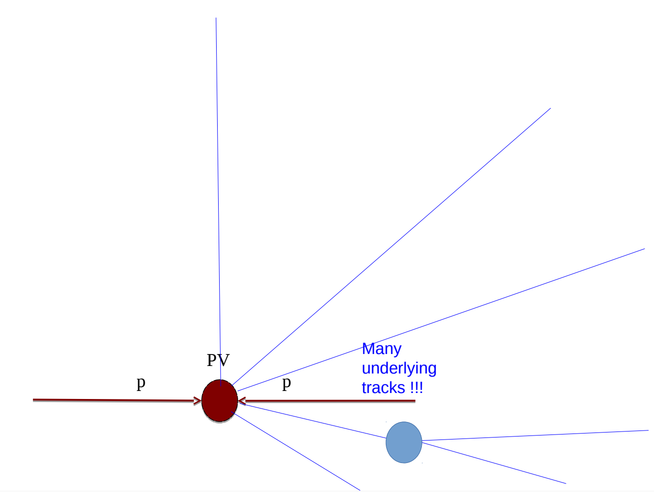

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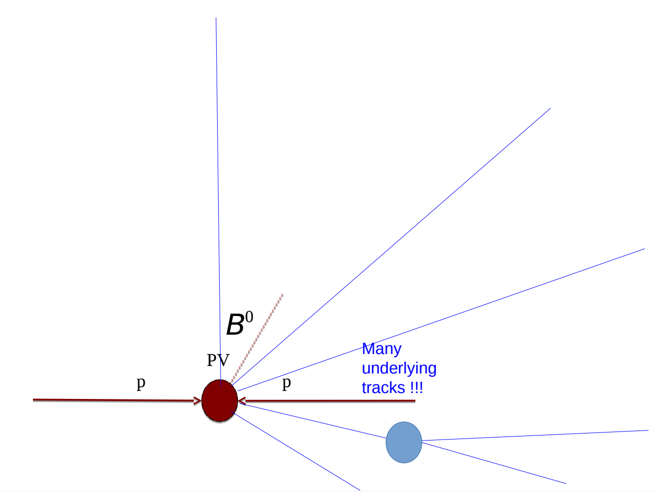

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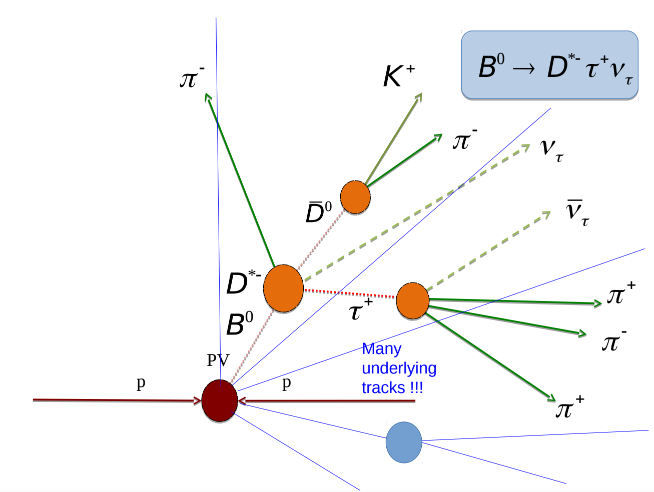

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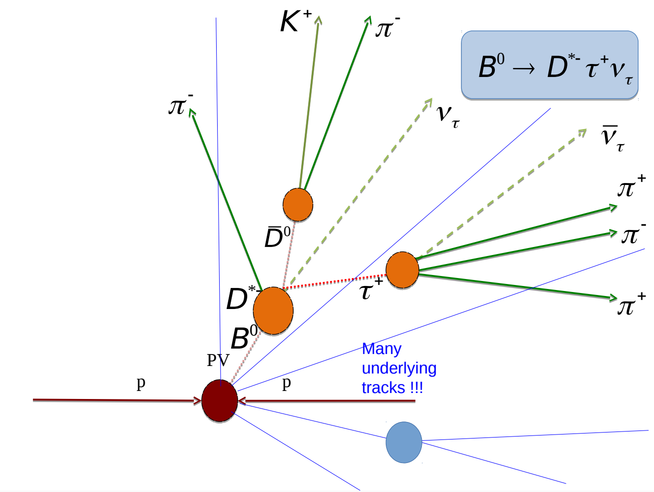

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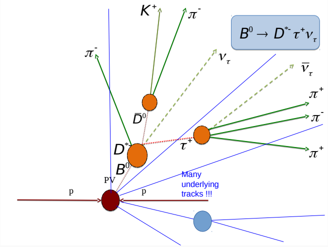
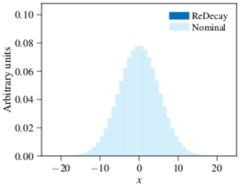


- Produce $N_{original} \times 100$ ("ReDecayed") events in a datasample
- 10-20 times faster, depending on mode
- Caveat: Events in 1 block may be correlated → Poisson errors not applicable → block-bootstrapping

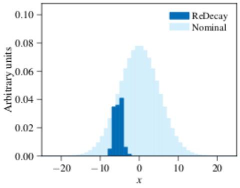
ReDecay blocks

Slide from D. Müller

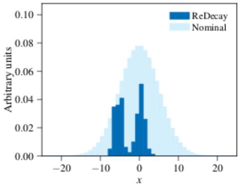
0 original events



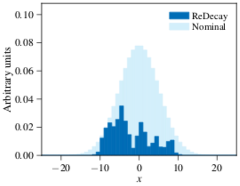
1 original events



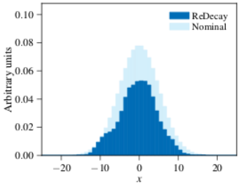
2 original events



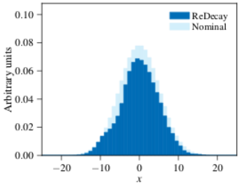
10 original events



500 original events

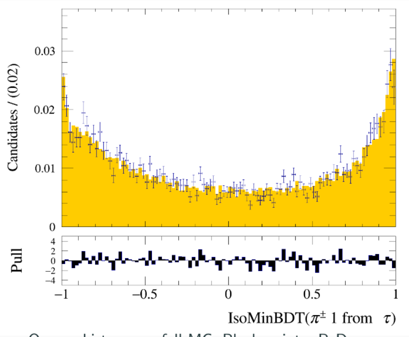


1000 original events



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

unofficial LHCb Simulation

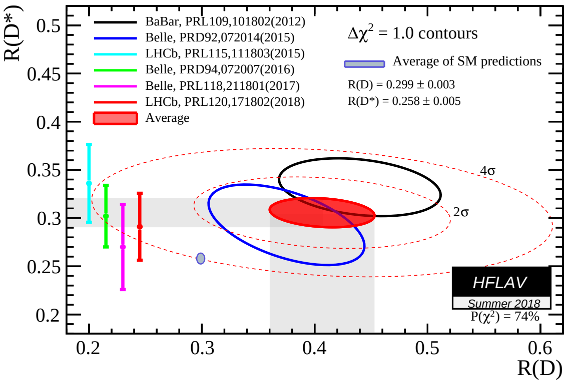


Orange histogram: full MC. Black points: ReDecay.

- Agreement of full ("slow") simulation (orange) and fast simulation (ReDecay) for a charged-isolation variable `IsoMinBDT` for the normalisation mode

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

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



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

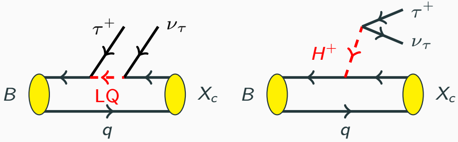
The papers "shrinking down" the $R(D)$–$R(D^*)$ anomalies

- J. E. Chavez-Saab *et al.*
  [https://doi.org/10.1103/PhysRevD.98.056014]
  "[...] longitudinal degree of freedom of the off-shell D^* [helps **reduce the tensions between SM and the world average** of $R(D^*)$] **from 3.7**σ **to 2.1**σ"
- A. Yaouanc *et al.* [arXiv:1806.09853 [hep-ph]]
  "[...] although the D^* is very narrow (one hundred of keV), the difference between the full D^* contribution to $B \to \bar{D}\pi\pi$ and its zero width limit [...], is surprisingly large: **several percent**."
- S. de Boer *et al.* [arXiv:1803.05881 [hep-ph]]
  Long-distance QED contributions: "[...] We find **theoretical predictions** for $R(D^+)^{\tau/\mu}$ and $R(D^0)^{\tau/\mu}$ can be **amplified by** $\sim$ **4% and** $\sim$ **3%**, respectively, for the soft-photon energy cut in the range 20-40 MeV"

Conclusions and prospects

Conclusions and prospects

- Interesting deviations suggesting Lepton Flavour Non-Universality observed in $R(D)/\ R(D^*)$ and $R(J/\Psi)$, $\mathbf{3.8\sigma}$ and $\approx \mathbf{2\sigma}$ away from SM
- So far, Run1 only. Run2: 5 $\times$ more statistics. Run3,4,5 planned!
- More analyses to come:
  - $b \to c\tau\nu$: $R(D^+)$, $R(D^0)$, $R(D_s^{(*)-})$, $R(\Lambda_c^{(*)})$, ...
  - $b \to u\tau\nu$: $R(\Lambda_b^0 \to p\tau\nu)$, $R(B \to pp\tau\nu)$, ...
- New observables to consider, *e.g.* angular analysis $\to$ NP spin structure
- Theoreticians are feverly cooking up various New Physics models.



Backup

$R(D^*)$ Run2 and beyond

$R(D^*)$ and $R(J/\Psi)$ in Upgrade II

Physics case for an LHCb Upgrade II

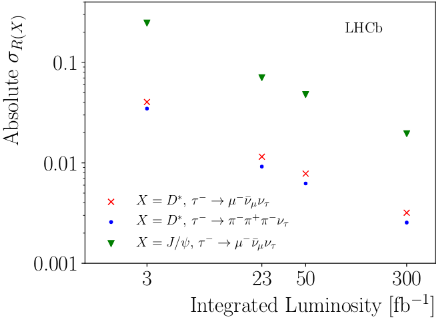


Figure 5.3: The projected absolute uncertainties on $\mathcal{R}(D^*)$ and $\mathcal{R}(J/\psi)$ (see Sect. 5.3.2) from the current sensitivities (at $3\,\mathrm{fb}^{-1}$) to $23\,\mathrm{fb}^{-1}$, $50\,\mathrm{fb}^{-1}$, and $300\,\mathrm{fb}^{-1}$.

- Assuming systematics scales down with $\int \mathcal{L}$
- Possible doing without the normalisation mode

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.

Flavour anomalies in general

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.

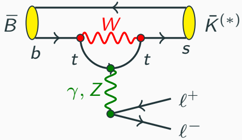
Many other interesting results exhibit no tension today, but put strong constraints on NP models.

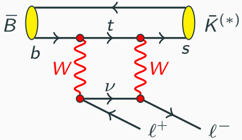
They remain fundamental for future searches, e.g.: γ, B^0-D^0-K^0-mixing, ϕ_s, $\sin 2\beta$, $B_s^0 \to \mu\mu$, $B \to X_s\gamma$, V_{cb}, $B \to \tau\nu$, CPV in charm, CLVF, $K \to \pi\nu\bar{\nu}$, ...

Two front LFU tests

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

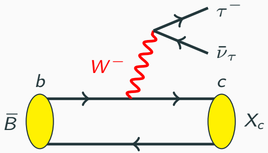
  - **FCNC $b \to s\ell\ell$**
  - Rare decay forbidden at the tree level
  - Very sensitive to NP contributions in the loops





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

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



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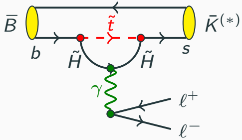

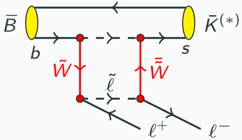

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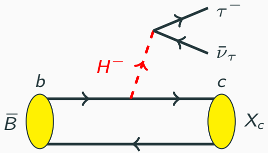
- Very well known in SM
- Possible NP coupling mainly to the 3rd family



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:

$d\Gamma/dq^2$	$\left[|H_+|^2 + |H_-|^2 + |H_0|^2\right]\left(1 + \frac{m_\ell^2}{2q^2}\right) + \frac{3}{2}\frac{m_\ell^2}{q^2}|H_t|^2$	
$1 - \mathcal{A}_{\lambda_\ell}$	$|H_+|^2 + |H_-|^2 + |H_0|^2 + 3|H_t|^2$	
$\mathcal{A}_{\mathrm{FB}}$	$|H_+|^2 - |H_-|^2 + 2\frac{m_\ell^2}{q^2}\Re\left[H_0 H_t^*\right]$	
$R_{L,T}$	$|H_+|^2 + |H_-|^2$	
A_5	$|H_+|^2 - |H_-|^2$	
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
$\mathcal{A}^D_{\rm FB}$	$\times$	$-$	$\star\star\star$	$-$	$\star$
$\mathcal{A}^D_{\lambda_\tau}$	$\times$	$-$	$\star\star\star$	$-$	$\star\star$
$\mathcal{A}^{D^*}_{\rm FB}$	$\star$	$\star\star\star$	$-$	$\star\star\star$	$\star$
$\mathcal{A}^{D^*}_{\lambda_\tau}$	$\times$	$\times$	$-$	$\star\star$	$\star$
$R_{L,T}$	$\times$	$\times$	$-$	$\star\star$	$\star\star$
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}	$\star\star$	$\star\star$	$-$	$\times$	$\star\star$
A_{11}	$\times$	$\times$	$-$	$\star\star$	$\star\star$

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:

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

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 $h_{A_1}(w)$, $R_{0,1,2}(w)$:

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

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

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

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

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:

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

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

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

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

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]

$$
\begin{aligned}
R_{D^*}(q^2) &= \frac{d\Gamma_\tau/dq^2}{d\Gamma_\ell/dq^2} = \\
&= \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left[\left(1 + \frac{m_\tau^2}{2q^2}\right) + \frac{3m_\tau^2}{2q^2} \frac{|H_{0t}|^2}{|H_{++}|^2 + |H_{--}|^2 + |H_{00}|^2}\right]
\end{aligned}
$$

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	$\mathbf{0.299 \pm 0.003}$	$\mathbf{0.258 \pm}$

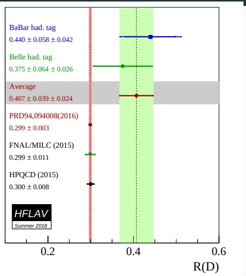
$R(D^*)$ and $R(D)$ summary

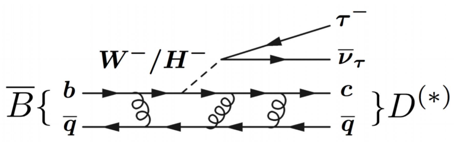
- Similarly to $R(D^*)$, the ratio is defined for D^- mesons:

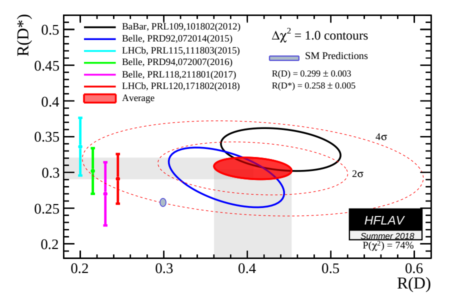
$$R(D) = \frac{\mathcal{B}(B^0 \to D^- \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^- \ell^+ \nu_\ell)}$$

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)	$> 6.6 \times 10^{26}$ 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 $(\tau \to 3\pi\nu_\tau)$

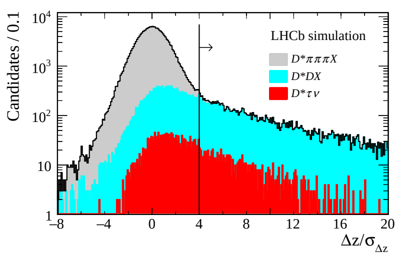
$R(D^*)$ **hadronic** $(\tau \to 3\pi\nu_\tau)$ [PRD 97,072013 2018]

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

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

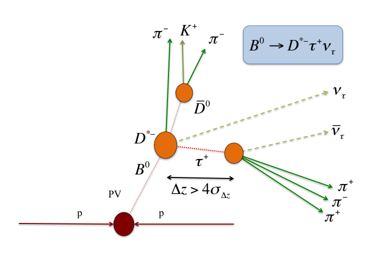
- Signal and normalization modes chosen to have the same final state
- $\mathcal{B}(\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau) = (9.31 \pm 0.05)\%$
- $\mathcal{B}(\tau^+ \to \pi^+\pi^-\pi^+\pi^0\bar{\nu}_\tau) = (4.62 \pm 0.05)\%$
- $N_{D^*3\pi}$ from unbinned fit to $D^*3\pi$ invariant mass
- $N_{D^*\tau\nu_\tau}$ 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]

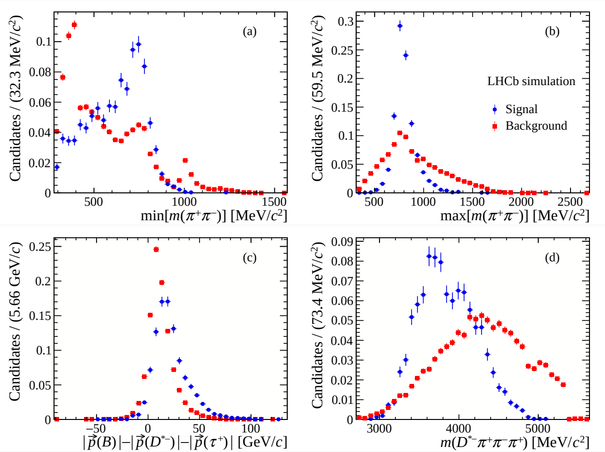


Distribution of the distance between the B^0 vertex and the 3π vertex along the beam direction, divided by its uncertainty, obtained using simulation. The grey area corresponds to the prompt background component, the cyan and red areas to double-charm and signal components, respectively. The vertical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

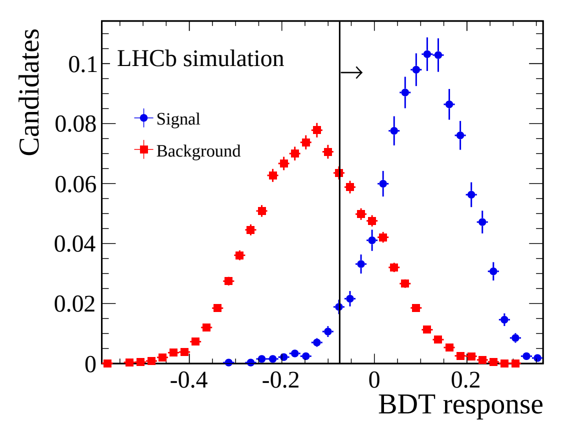


$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$). Anti-D_s^+ BDT [PRD 97,072013 2018]



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.

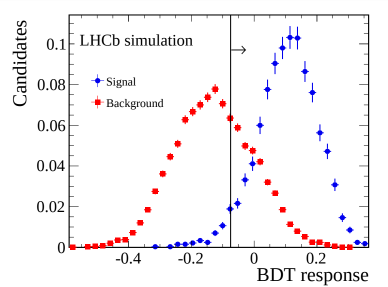
Main $R(D^*)$ backgrounds: $X_b \to D^{*-} D_s^+(X)$

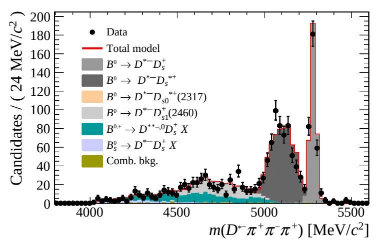
Rejected with a **Boosted Decision Tree** using

- 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).

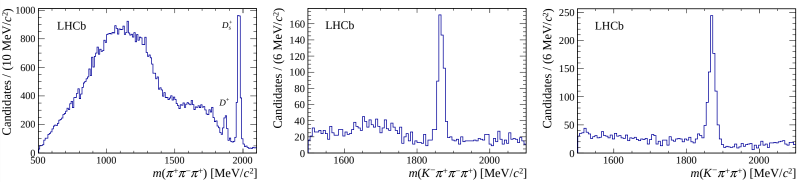
Clear separation between D_s, D_s^* and D_s^{**}





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

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

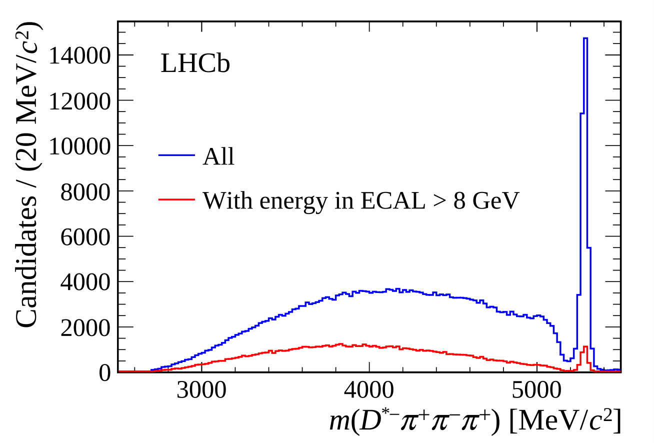


Left: Distribution of the 3π mass for candidates after the detached-vertex requirement. The D^+ and D_s^+ mass peaks are indicated.

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)

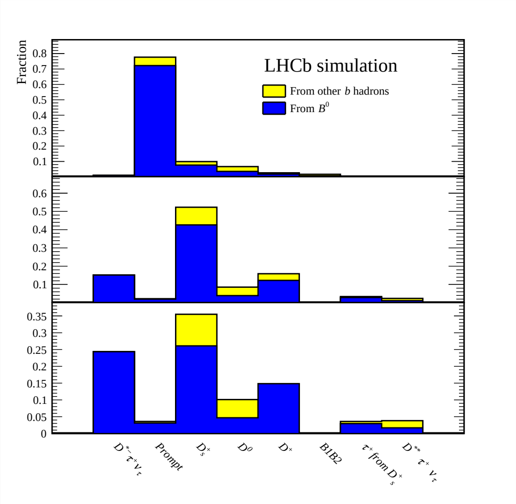
Right: Distribution of the $K^-\pi^+\pi^+$ mass for D^+ candidates passing the signal selection, where the negative pion has been identified as a kaon and assigned the kaon mass. (antiPID)

$R(D^*)$ 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]



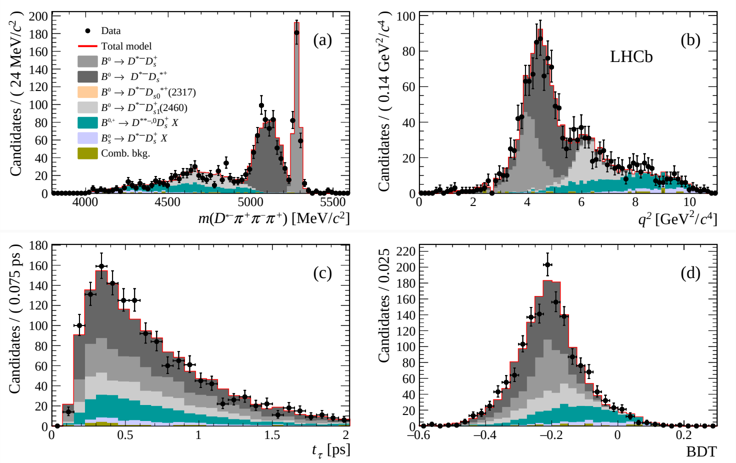
Composition of an inclusive simulated sample where a D^{*-} and a 3π system have been produced in the decay chain of a $b\bar{b}$ pair from a pp collision. Each bin shows the fractional contribution of the different possible parents of the 3π system (blue from a B^0, yellow for other b hadrons): from 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.

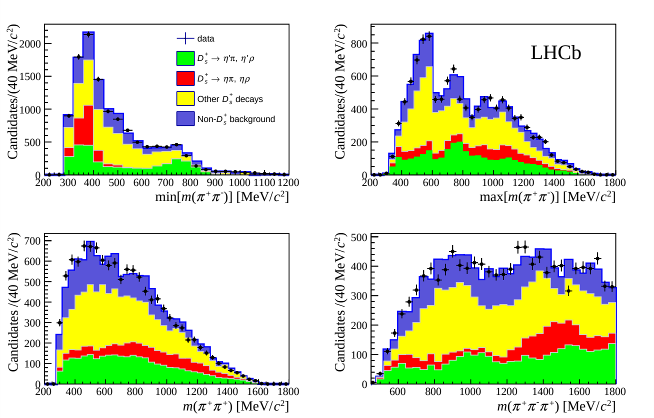
(Bottom) For candidates populating the last 3 bins of the BDT distribution.

$R(D^*)$ 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.

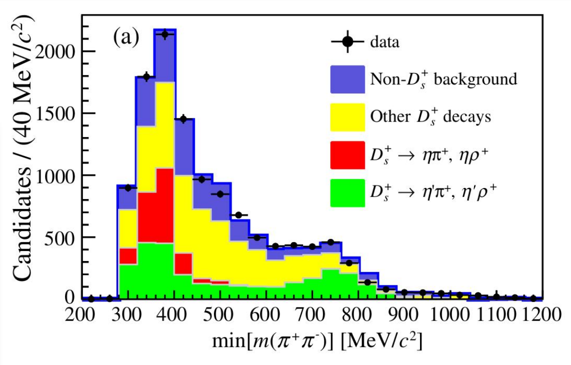
D_s^+ decays with at least 1 pion from η (red) or η' (green): $\eta^{(\prime)}\pi^+$, $\eta^{(\prime)}\rho^+$

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_{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

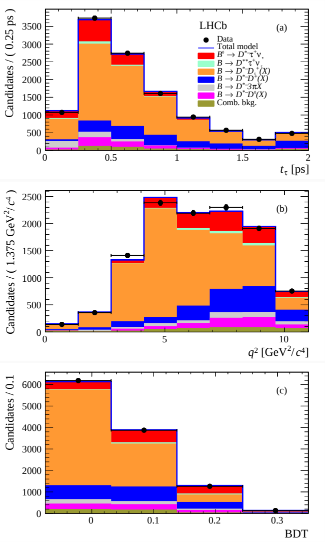
$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$) [PRD 97,072013 2018]

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	$f_{D^0}^{v_1 v_2} \times N_{D^0}^{\rm sv}$
$B \to D^{*-}D^0X$ 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_{sig}	1296 ± 86	
$f_{\tau\to 3\pi\nu}$	0.78	0.78 (fixed)
$f_{D^{**}\tau\nu}$	0.11	0.11 (fixed)
$N_{D^0}^{\mathrm{sv}}$	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)
$N_{\mathrm{not}D^*}$	243	243 (fixed)

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

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

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

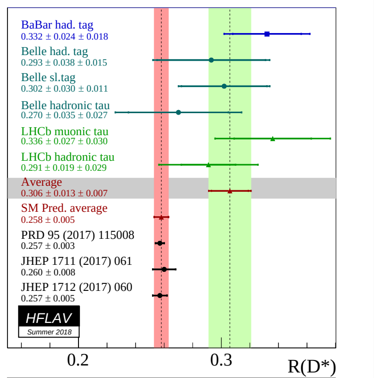
Contribution	Value in %
$\mathcal{B}(\tau^+ \to 3\pi\overline{\nu}_\tau)/\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\overline{\nu}_\tau)$	0.7
Form factors (template shapes)	0.7
Form factors (efficiency)	1.0
τ polarization effects	0.4
Other τ decays	1.0
$B \to D^{**}\tau^+\nu_\tau$	2.3
$B_s^0 \to D_s^{**}\tau^+\nu_\tau$ 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

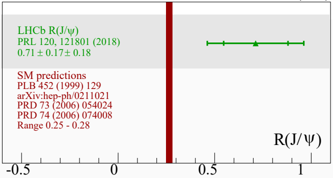
$R(D^*)$ hadronic ($\tau \to 3\pi\nu_\tau$) Improvement of systematics in the future [PRL 120, 171802 2018]

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

- 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.

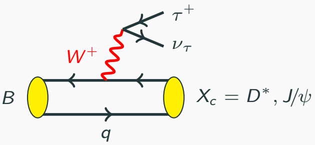
$R(D^*)$ and $R(J/\psi)$ summary



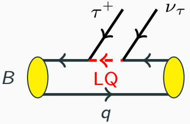


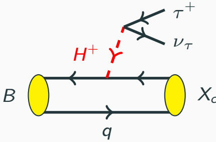
3 experiments, 7 measurements, different analysis techniques: ALL $R(D^*)$ and $R(J/\psi)$ measurements lie ABOVE the SM expectations.

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

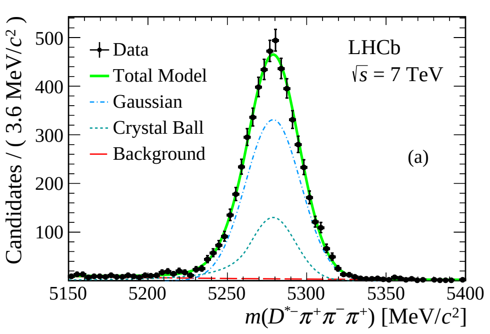


Possible NP contributions ?





$B^0 \to D^{*-}\pi^+\pi^-\pi^+$ normalisation yield



- Obtained: $N_{norm} = 17660 \pm 143\,(\text{stat}) \pm 64\,(\text{syst}) \pm 22(sub)$ events
- Signal fit: Gaussian + Crystal Ball (to account for radiative photons)

Longitudinal effects on $R(D^*)$

J. E. Chavez-Saab *et al.*

[https://doi.org/10.1103/PhysRevD.98.056014]

The complete four-body amplitude, on the other hand, is given by

$$M = M_{3\mu} D^{\mu\nu} M_{2\nu},$$

where $D^{\mu\nu}$ is the D^* propagator that, upon considering the absorptive correction (dominated by the $D\pi$ mode as discussed before), can be set in terms of the transverse and longitudinal part as follows [15–17]:

$$D^{\mu\nu} = \frac{-iT^{\mu\nu}}{p_{D^*}^2 - m_{D^*}^2 + i\mathrm{Im}\Pi_T} + \frac{iL^{\mu\nu}}{m_{D^*}^2 - i\mathrm{Im}\Pi_L}, \qquad (4)$$

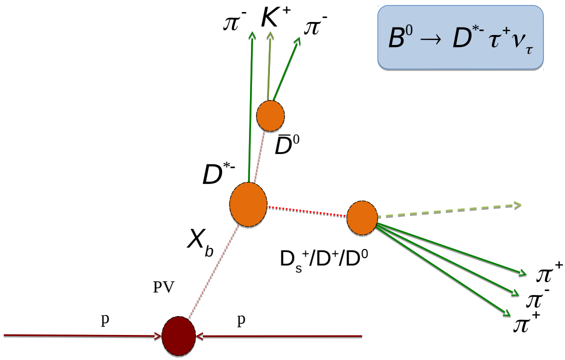
with the corresponding projectors

$$T^{\mu\nu} \equiv g^{\mu\nu} - \frac{p_{D^*}^\mu p_{D^*}^\nu}{p_{D^*}^2} \quad \text{and} \quad L^{\mu\nu} \equiv \frac{p_{D^*}^\mu p_{D^*}^\nu}{p_{D^*}^2}.$$

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

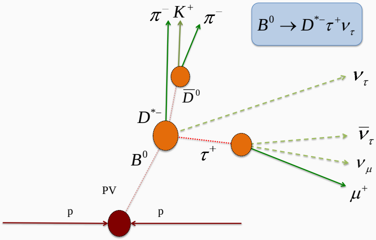
Challenge: D-mesons may live long enough to be mistaken for the τ

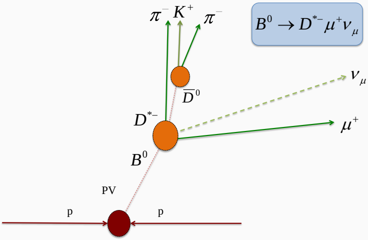
- $X_b \to D^{*-} D_s^+ X \sim 10\times$ signal
- $X_b \to D^{*-} D^+ X \sim 1\times$ signal
- $X_b \to D^{*-} D^0 X \sim 0.2\times$ signal



$R(D^*)$ muonic

$R(D^*)$ muonic $(\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau)$ [PRL 115, 112001 (2015)]





- $R(D^*) = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}$ with $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$, $\mathcal{B}(\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau) = (17.39 \pm 0.04)\%$
- Normalization mode with the *same visible final state*
- 3 neutrinos for the signal mode and one for the normalisation: no narrow peak to fit
- Separate τ and μ via a $3D$ binned template fit, in the B rest frame, on:
  1. $m^2_{\rm miss} = (p^\mu_B - p^\mu_{D*} - p^\mu_\mu)^2$ missing mass squared
  2. E^*_μ muon energy
  3. $q^2 = (p^\mu_B - p^\mu_{D*})^2$ squared 4-momentum transfer to the lepton system
- Background and signal shapes extracted from control samples and simulations validated against data

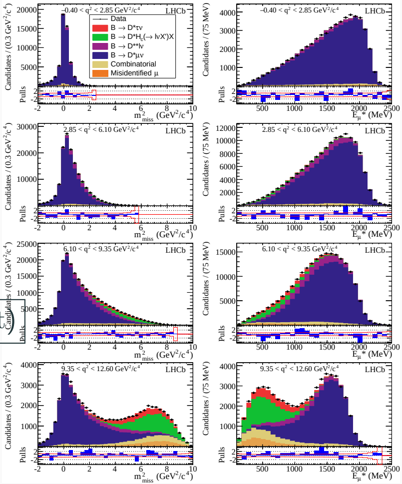
$R(D^*)$ muonic $(\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau)$ [PRL 115, 112001 (2015)]

- Signal more visible in the high q^2 bins (red)
- Backgrounds: feed-down from excited D states, double charm DD where one D decays semileptonically, combinatorial, muon mis-ID

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

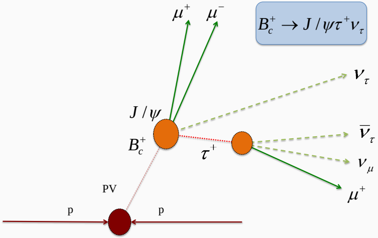
1.9σ above SM

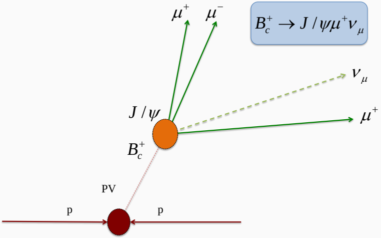
- Dominant systematics: size of simulation sample → will be improved in the next iteration



$R(J/\psi)$

$B_c^+ \to J/\psi \tau^+ \nu$: $R_{J/\psi}$ [PRL 120, 121801 (2018)]





- $R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\, \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\, \mu^+ \nu_\mu)}$, $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$
- B_c^+ decay form factors unconstrained experimentally: theoretical prediction not yet precise $R^{\text{theo}}(J/\psi) \in [0.25, 0.28]$

  [PLB452 (1999) 120, arXiv:0211021, PRD73 (2006) 054024, PRD74 (2006) 074008]
- Low B_c^+ production rate and short lifetime, but no "flying D background" and nice J/ψ
- Like in $R(D^*)$, use m^2_{miss}, E^*_μ and q^2. Add information from B_c^+ decay time

$B_c^+ \to J/\psi\,\tau^+\nu : R_{J/\psi}$ [PRL 120, 121801 (2018)]

components are represented by a template distribution derived from control samples or simulations validated against data

- Main background is $b \to J/\psi +$ mis-ID hadron
- First evidence for the decay $B_c^+ \to J/\psi\,\tau^+\nu_\tau$ (3σ)

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

About 2σ above SM

- Main systematics: form factor and size of simulation sample