Recent results using semileptonic decays with LHCb

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on behalf of the LHCb collaboration

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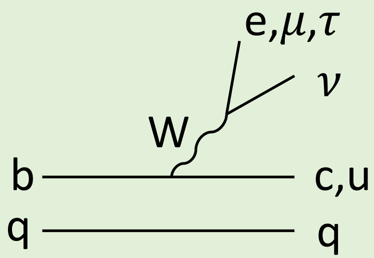
Semileptonic *B* decays at the LHC

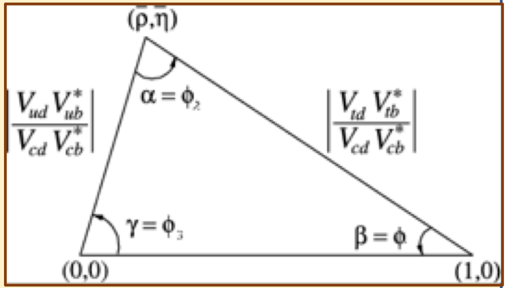
- B mesons copiously produced at LHCb: **large *B* production cross-section.**
- Also, large number of **Λ_b^0, B_s^0** and **B_c^+** hadrons produced.
- High branching fractions, $\mathcal{B}(B\to X\ell\nu_\ell)\simeq 10\%$: **tree level transition** mediated by a $W^\pm$ boson in the SM.
- Theoretically clean: only **one hadronic current**, parameterised in terms of scalar functions (**form-factors**).



- Partially reconstructed signal: difficult to reconstruct due to **missing neutrino(s)**.
- No beam energy **constraint** (as in B-factories).

Semileptonic (SL) B decays provide powerful probes for:

- **Testing the SM**. SL B decays involving **electrons** and **muons** expected to be free of BSM contributions: Used to measure CKM parameters **$|V_{ub}|$** and **$|V_{cb}|$**.
- **Searching for physics BSM**: decays involving **τ** (semitauonic) sensitive to contributions BSM.



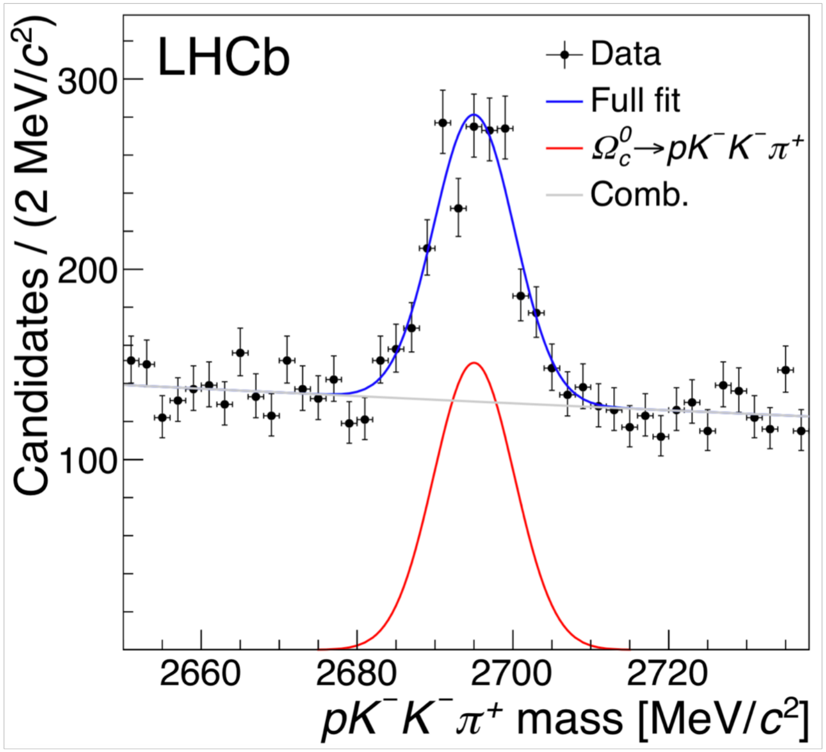
Outline

- Measurement of the charmed baryons lifetime using semileptonic decays. [PRL 121, 092003 (2018) , LHCb-PAPER-2019-008]
- Determination of $|V_{ub}|/|V_{cb}|$ and search for the decay $B^- \rightarrow \mu^+\mu^-\mu^-\nu_\mu$.
[Nature Physics 11 743-747 (2015) , arXiv:1812.06004]
- Lepton Flavor Universality tests using semitauonic B decays.
[PRL 115, 111803 (2015) , PRL 120, 171802 (2018) , PR D97, 072013 (2018) , PRL 120, 121801 (2018)]

Charmed baryons lifetimes

- Lifetime of charmed baryons are known with **less precision** than charmed mesons.
- They can be used to test Heavy Quark Expansion (**HQE**).
- A lifetime **hierarchy** is expected: $\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$.
- Previous measurements **consistent** with this hierarchy.

- Ω_c^0 reconstructed using SL $\boldsymbol{\Omega_b^- \to \Omega_c^0 \mu^- \nu_\mu X}$ decays with $\boldsymbol{\Omega_c^0 \to pK^-K^-\pi^+}$.
- Measured ratio $\boldsymbol{\tau(\Omega_c^0)/\tau(D^+)}$ with $D^+ \to K^-\pi^+\pi^+$ to reduce systematic uncertainties.
- Analysis using LHC run-1 data: 1 fb^{-1} at 7 TeV and 2 fb^{-1} at 8 TeV.
- Much larger signal wrt previous experiments: **978 ± 60 $\boldsymbol{\Omega_c^0}$ candidates**.

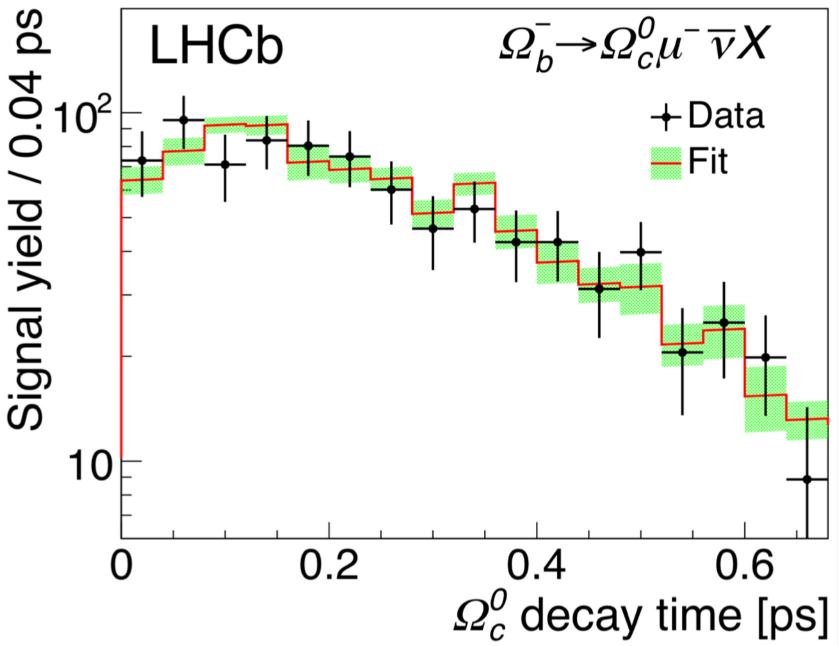


[PRL 121, 092003 (2018)]

Charmed baryons lifetimes

- Measured lifetime:

  $\tau(\Omega_c^0) = 268 \pm 21(\text{stat}) \pm 10\ (\text{syst}) \pm 2\ (D^+)$ fs.
- Four times larger than, and **inconsistent** with world average: **$\tau^{PDG}(\Omega_c^0) = 69 \pm 12$ fs.**

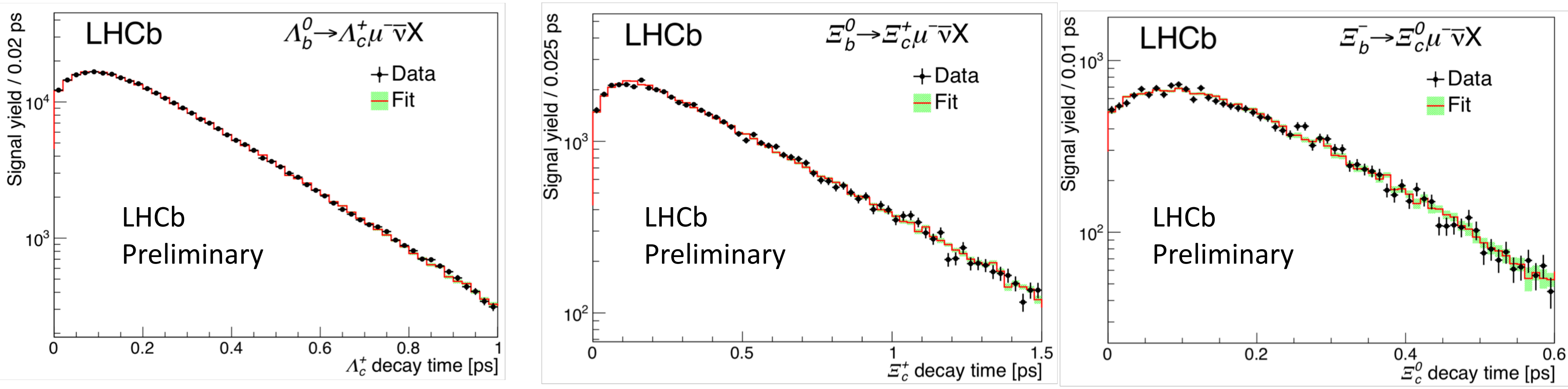


- Same method can be used to measure the lifetime of other charmed baryons:
  - $\boldsymbol{\Lambda_c^+ \to pK^-\pi^+}$ from $\Lambda_b^0 \to \Lambda_c^+\mu^-\nu_\mu X$ decays.
  - $\boldsymbol{\Xi_c^+ \to pK^-\pi^+}$ from $\Xi_b^0 \to \Xi_c^+\mu^-\nu_\mu X$ decays.
  - $\boldsymbol{\Xi_c^0 \to pK^-K^-\pi^+}$ from $\Xi_b^- \to \Xi_c^0\mu^-\nu_\mu X$ decays.

[PRL 121, 092003 (2018)]

Charmed baryons lifetimes

NEW



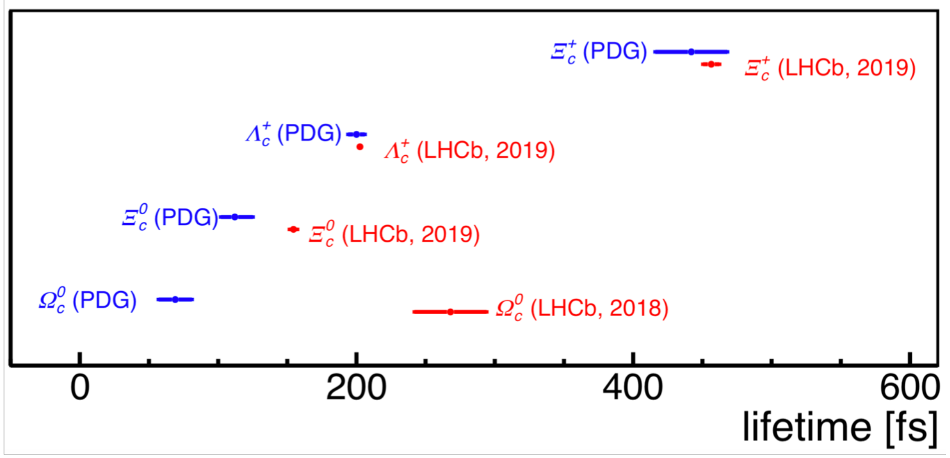
$\tau\,(\Lambda_c^+) = 203.5 \pm 1.0\,\text{(stat)} \pm 1.3\,\text{(syst)} \pm 1.4\,(D^+)$ fs

$\tau\,(\Xi_c^+) = 456.8 \pm 3.5\,\text{(stat)} \pm 2.9\,\text{(syst)} \pm 3.1\,(D^+)$ fs

$\tau\,(\Xi_c^0) = 154.5 \pm 1.7\,\text{(stat)} \pm 1.6\,\text{(syst)} \pm 1.0\,(D^+)$ fs

⟸ LHCb Preliminary

[LHCb-PAPER-2019-008]



- **Ξ_c^0 lifetime 3.3σ above WA.**
- **Ω_c^0 lifetime incompatible with WA.**
- **Need to understand better hierarchy of charmed baryons lifetime.**

Determination of $|V_{ub}|/|V_{cb}|$

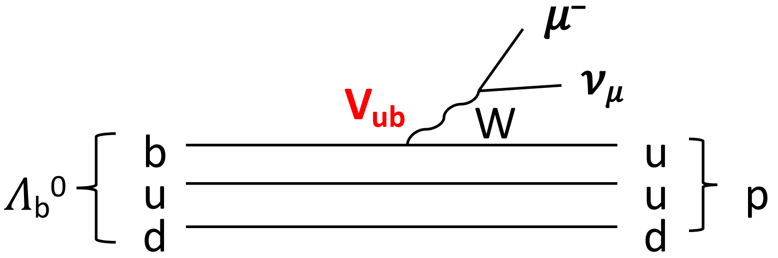
- $|V_{ub}|/|V_{cb}|$ accessible by measuring the ratio of branching fractions:

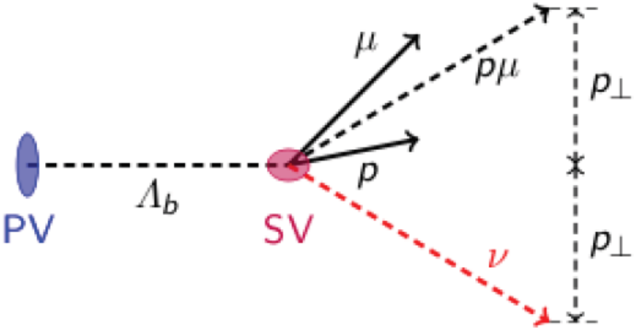
$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} R_{\mathrm{FF}}$$

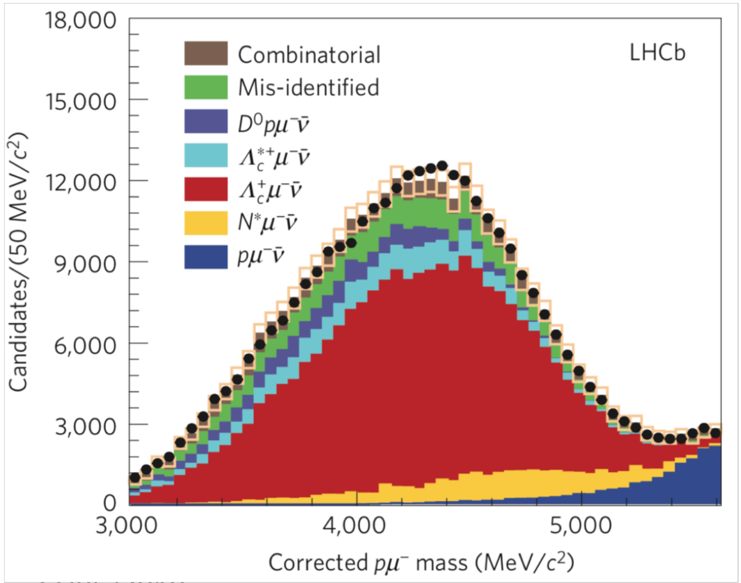
(R_{FF} from Lattice)

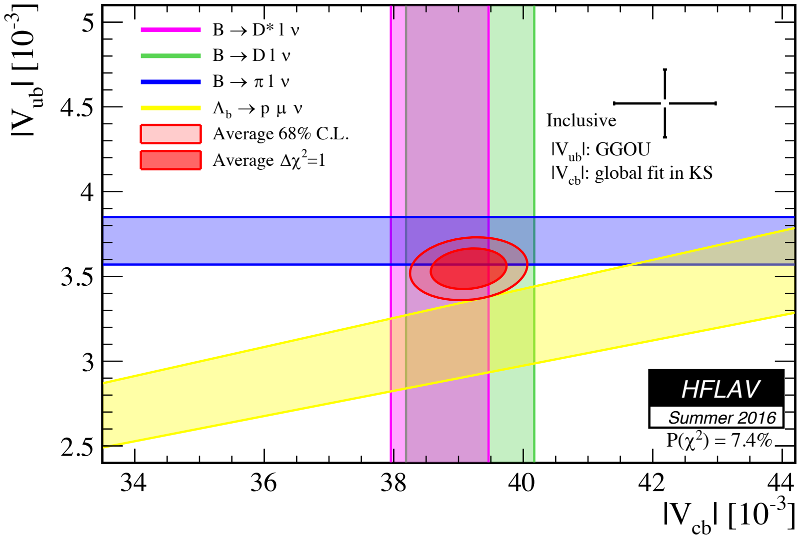
- Measurement from a 1D fit to the **corrected mass**:

$$M_{corr} = \sqrt{M_{p\mu}^2 + p_\perp^2} + p_\perp$$









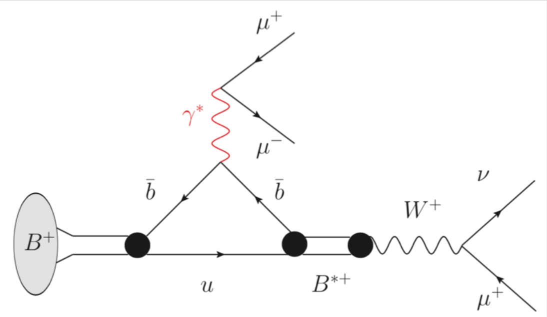
[Nature Physics 11 743-747 (2015)]

Search for $B^- \rightarrow \mu^+\mu^-\mu^-\nu_\mu$ decay

- Similar method used for $B^- \rightarrow \mu^+\mu^-\mu^-\nu_\mu$ decays:

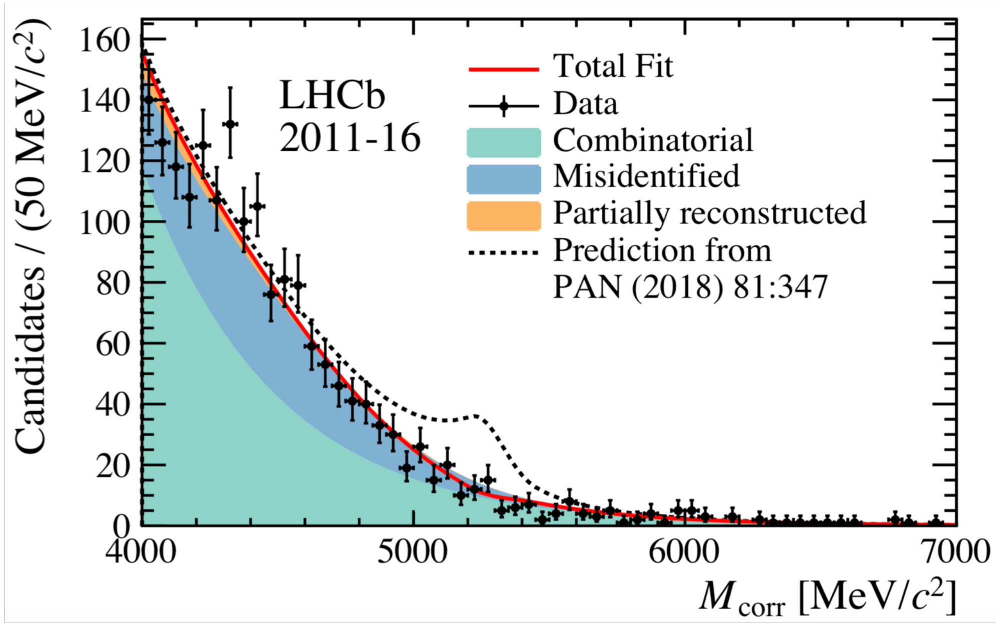
  ⇒ fit to $\mathbf{M}_{\mathbf{corr}}$.
- Very suppressed decay with BF $\propto |V_{ub}|^2$.
- Theoretical prediction (vector-meson dominance):

  $\mathcal{B}(B^- \rightarrow \mu^+\mu^-\mu^-\nu_\mu) \sim 1.3 \times 10^{-7}$ (PAN (2018) 81, 347).



- Signal normalised to $B^+ \rightarrow J/\psi K^+$.
- Selected $M_{\mu\mu}^{\min} < 980$ MeV/c^2 .
- 4.7 fb^{-1} of 2011-2016 data.
- No signal found:

  ⇒ $\boldsymbol{\mathcal{B}(B^- \rightarrow \mu^+\mu^-\mu^-\nu_\mu) < 1.6 \times 10^{-8}}$.



[arXiv:1812.06004]

Prospects on $|V_{ub}|$ and $|V_{cb}|$

- $|V_{ub}|/|V_{cb}|$ from the ratio $B_s^0 \longrightarrow K^+\mu\nu$ to $B_s^0 \longrightarrow D_s^+\mu\nu$.

    - Precise form-factors calculation possible due to relatively large *s* quark mass.
    - Large $B_s^0 \longrightarrow D_s^+\mu\nu$ yield, but …
    - Large feed-down from excited D_s meson decays with neutrals: $D_s^* \longrightarrow D_s\gamma$.
    - $B_s^0 \longrightarrow K^+\mu\nu$ signal rate ~1 order of magnitude smaller than $\Lambda_b^0 \longrightarrow p\mu^-\nu_\mu$.

- Good prospects to perform a differential measurement in many q^2 bins with $\Lambda_b^0 \longrightarrow p\mu^-\nu_\mu$ decays. Requires larger data samples.

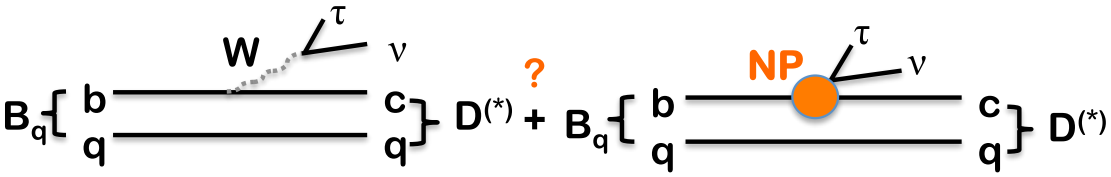
- Measurements in $B_c^+ \longrightarrow D^0\mu\nu$ decays can provide a competitive measurement of $|V_{ub}|$: 30,000 events expected at the end of LHCb Upgrade II (300 fb^{-1}).

- **Expected ~1% precision in $|V_{ub}|/|V_{cb}|$ with LHCb Upgrade II dataset**.

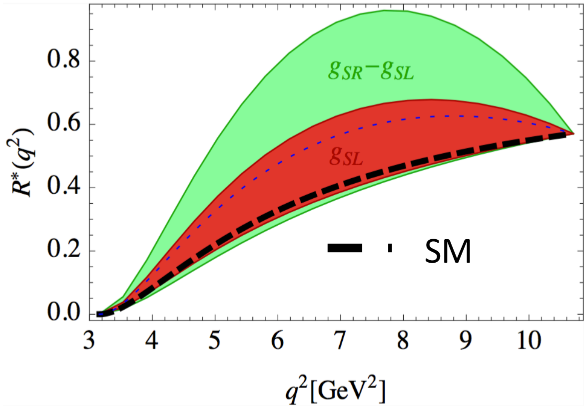
[arXiv:1808.08865]

Tests of LFU using SL B decays

- In the SM, amplitudes for processes involving e, μ, τ must be identical up to effects depending on lepton mass: Lepton Flavor Universality (LFU).
- Observation of violations of LFU would be a sign for new physics (NP).



[PRD 85 094025 (2012)]



- Comparison between semitauonic (τ) and semimuonic (μ) decays is sensitive to NP, which could modify branching ratios and angular distributions.

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

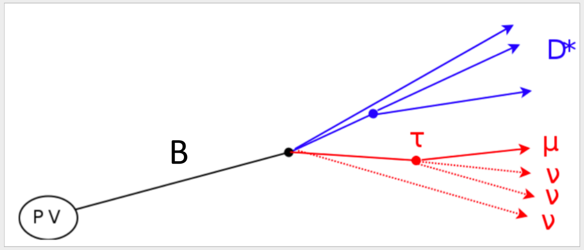
- $R(D^{(*)})$ very clean SM prediction due to partial cancellation of form factors uncertainties in the ratio.

	$R_{SM}(D)$	$R_{SM}(D^*)$
PRD94 (2016) 9, 094008	0.299 ± 0.003	
PRD95 (2017) 11, 115008	0.299 ± 0.003	0.257 ± 0.003
JHEP 1711 (2017) 061		0.260 ± 0.008
JHEP 1712 (2017) 060	0.299 ± 0.004	0.257 ± 0.005

R(D*) with $\tau^- \longrightarrow \mu^- \nu_\mu \nu_\tau$ decays

- R(D*) measured using $B^0 \longrightarrow D^{*-}\tau^+\nu_\tau$ decays with $\boldsymbol{\tau \longrightarrow \mu\nu_\mu\nu_\tau}$ and $D^{*-} \longrightarrow D^0(\longrightarrow K\pi)\pi^-$.
- **Approximation** needed to estimate the B momentum p_B.
  - B boost along z >> boost of decay products in B rest frame.

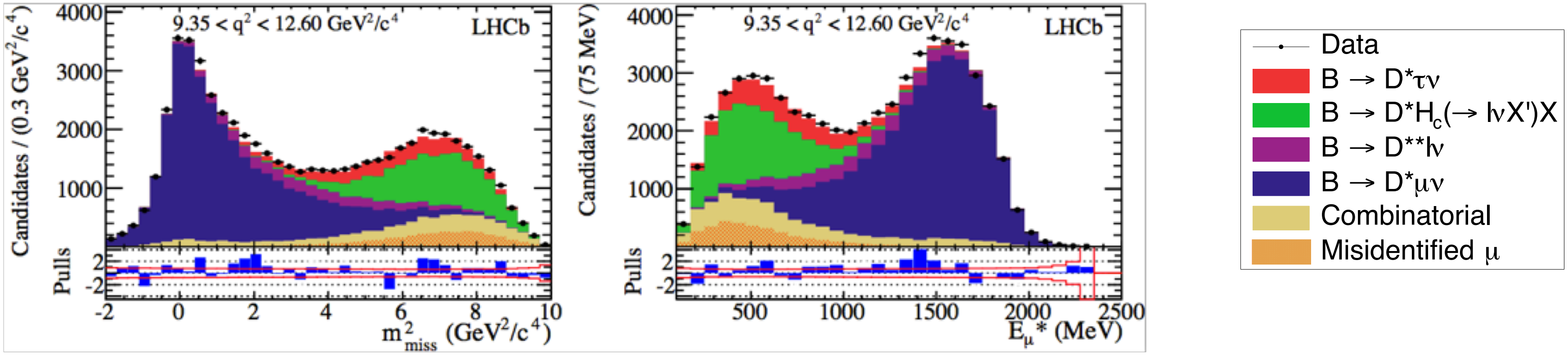
$$(\gamma\beta_z)_B = (\gamma\beta)_{D^*\mu} \Rightarrow (p_z)_B = \frac{m_B}{m(D^*\mu)}(p_z)_{D^*\mu}$$



- **~8% resolution on $\mathbf{p_B}$** enough to preserve signal and background discrimination.
- R(D*) obtained from 3D template fit to **$\mathbf{m^2_{miss}}$, $\mathbf{E_\mu^*}$ and $\mathbf{q^2}$**:

R(D*) = 0.336 ± 0.027 (stat, 8.0%) ± 0.030 (syst, 8.9%)

(2.1**σ** above SM)



- Largest systematic uncertainties are the size of simulated samples and μ↔π misID.

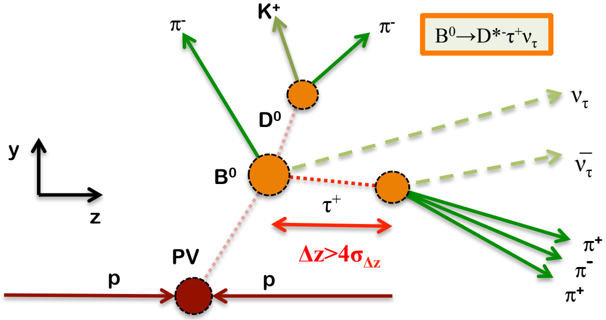
[PRL 115, 111803 (2015)]

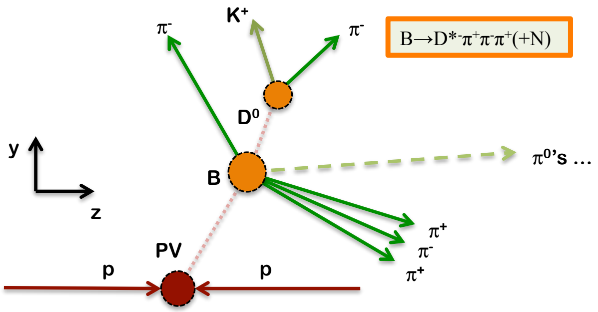
R(D*) with $\tau^- \longrightarrow \pi^-\pi^+\pi^-\nu_\tau$ decays

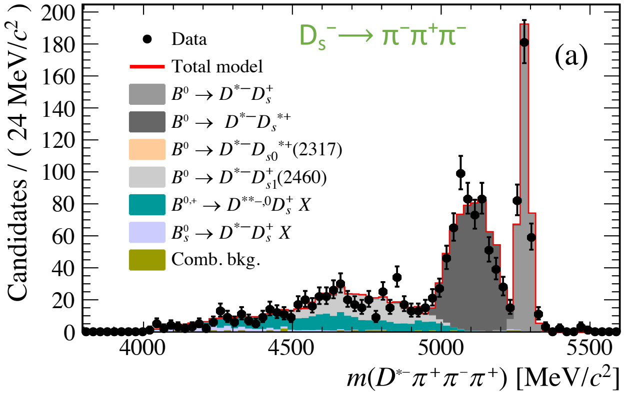
- R(D*) measured using $B^0 \longrightarrow D^{*-}\tau^+\nu_\tau$ decays with $\boldsymbol{\tau^- \longrightarrow \pi^-\pi^+\pi^-\nu_\tau}$ and $D^{*-} \longrightarrow D^0(\longrightarrow K\pi)\pi^-$.
- $\boldsymbol{B^0 \longrightarrow D^{*-}\pi^+\pi^-\pi^+}$ used as normalisation mode.

$$R(D^*) = \frac{N_{sig}}{N_{norm}} \times \frac{\varepsilon_{norm}}{\varepsilon_{sig}} \times \frac{1}{\mathcal{B}(\tau \to \pi^+\pi^+\pi^-(\pi^0)\nu_\tau)} \times \left(\frac{\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^+\pi^-)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)}\right)_{ext}$$

- **Most abundant background $\boldsymbol{B \longrightarrow D^{*-}\pi^+\pi^-\pi^+X}$** suppressed by requiring a significant displacement between the τ and B vertices.
- Main **remaining background** due to $\boldsymbol{B \longrightarrow D^{*-}DX}$ decays, with $D \longrightarrow \pi^+\pi^-\pi^+X$ (D lifetime).
- This doubly-charmed background can be controlled using **control samples**:
  - $D_s^- \longrightarrow \pi^-\pi^+\pi^-$, $D^- \longrightarrow K^+\pi^-\pi^-$ and $D^0 \longrightarrow K^+\pi^-\pi^+\pi^-$.
- $B \longrightarrow D^{*-}DX$ decays further suppressed using a **BDT** (includes kinematic+isolation variables).



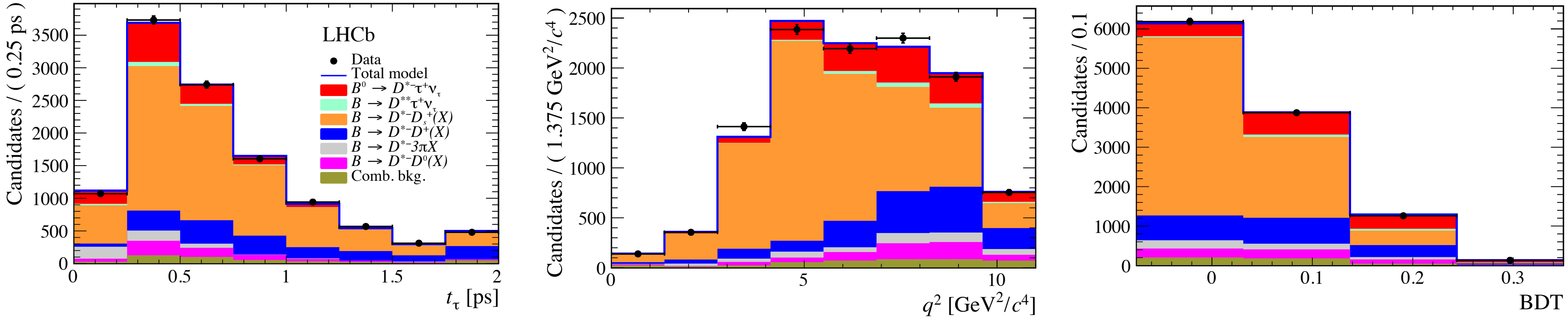




[PRL 120, 171802 (2018)] [PRD 97, 072013 (2018)]

R(D^*) with $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$ decays

- Signal yield extracted from a **3D fit** to **q^2**, **τ decay time** and **BDT**: **N_{sig} = 1296 ± 86**.
- Normalisation yield from a fit to **$M(D^{*-}\pi^+\pi^-\pi^+)$** invariant mass: **N_{norm} = 17080 ± 143**.



Using 2017 WA:

$$\mathcal{B}(B^0 \to D^{*-}\pi^+\pi^+\pi^-) = (7.21 \pm 0.28)\times 10^{-3}$$
$$\mathcal{B}\left(B^0 \to D^{*-}\mu^+\nu_\mu\right) = (4.88 \pm 0.10)\times 10^{-2}$$

⇒ R(D^*) = 0.291 ± 0.019 ± 0.026 ± 0.013

Recently, HFLAV provided separated averages for B^0 and B^+ semileptonic decays:

$$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = (5.05 \pm 0.02 \pm 0.14)\times 10^{-2}$$
$$\mathcal{B}(B^+ \to \overline{D}^{*0}\ell^+\nu_\ell) = (5.66 \pm 0.07 \pm 0.21)\times 10^{-2}$$

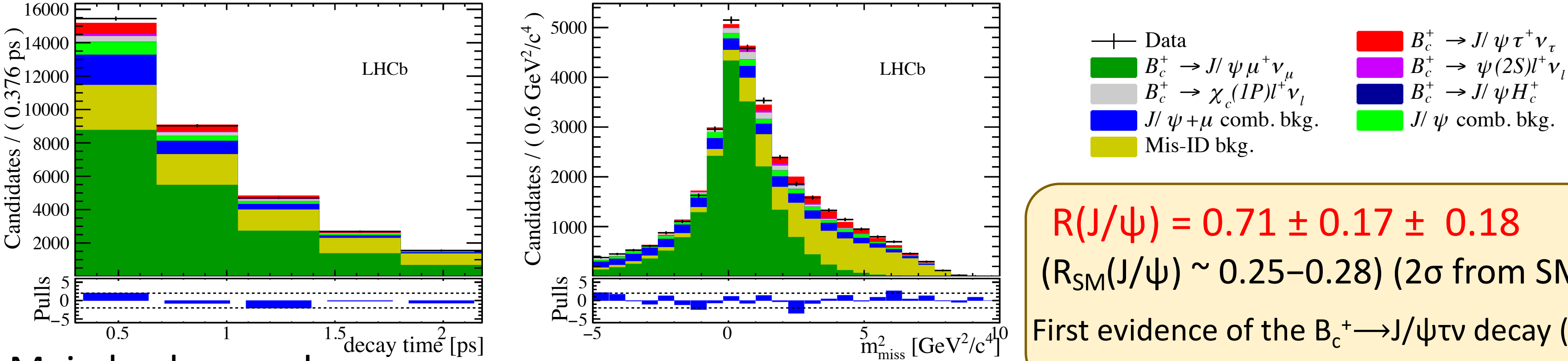
R(D^*) changes to ⇒ **R(D^*) = 0.280 ± 0.018 ± 0.029**

New updated result closer to SM prediction (<1**σ**)

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

R(J/ψ) with $\tau^- \longrightarrow \mu^- \nu_\mu \nu_\tau$ decays

- Goal: measurement of $R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau \nu)}{\mathcal{B}(B_c^+ \to J/\psi \mu \nu)}$ using $\tau^- \longrightarrow \mu^- \nu_\mu \nu_\tau$ decays.
- Only possible at LHCb (B_c^+ only at LHC).
- Same reconstruction (p_B) method as in muonic R(D^*) measurement.
- R(J/ψ) obtained from a 3D template fit to B_c^+ decay time, m_{miss}^2 and Z(E_μ^*,q^2). Form-factors obtained from a sample enriched in normalisation decays.



R(J/ψ) = 0.71 ± 0.17 ± 0.18

(R_{SM}(J/ψ) ~ 0.25−0.28) (2σ from SM)

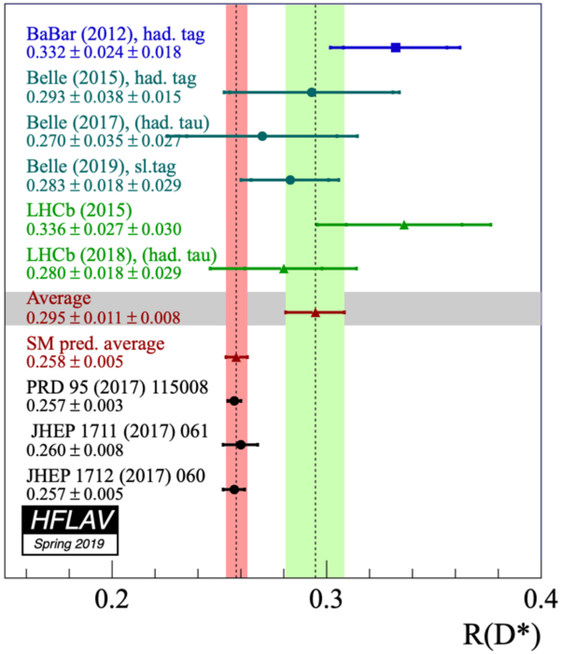
First evidence of the $B_c^+ \longrightarrow J/\psi \tau \nu$ decay (3σ)

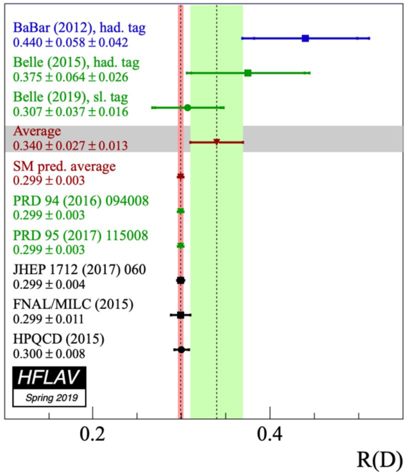
- Main backgrounds:
  - $B_c^+ \longrightarrow J/\psi \mu \nu$ (normalisation), $B_c^+ \longrightarrow \psi(2S) \mu \nu$, $B_c^+ \longrightarrow J/\psi D(\longrightarrow \mu \nu X)X$.
  - Hadron misidentified as a muon.
  - combinatorial background (J/ψ and μ not from same B).
- Systematic uncertainties dominated by knowledge of form-factors and the size of the simulation samples.

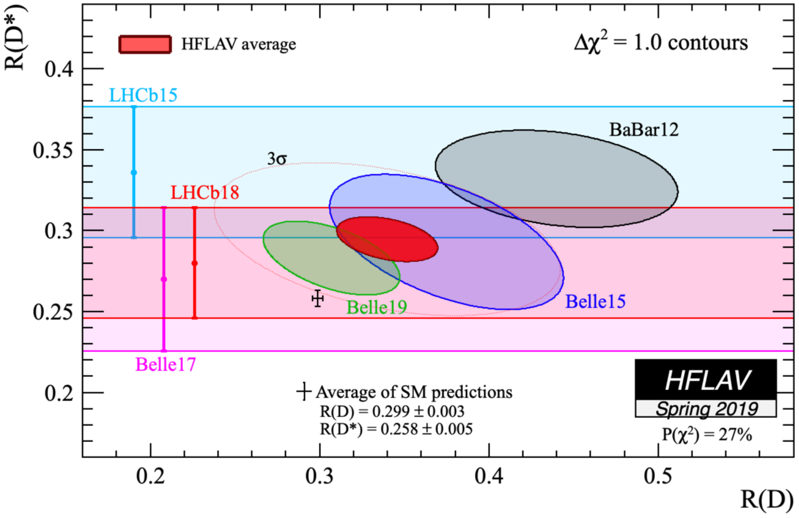
[PRL 120, 121801 (2018)]

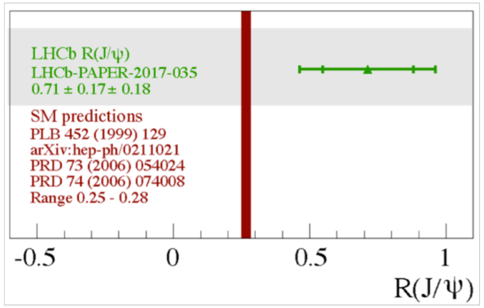
Summary on R(X_c)

New R(D)/R(D*) combined measurement by Belle using SL tagging available in arXiv:1904.08794





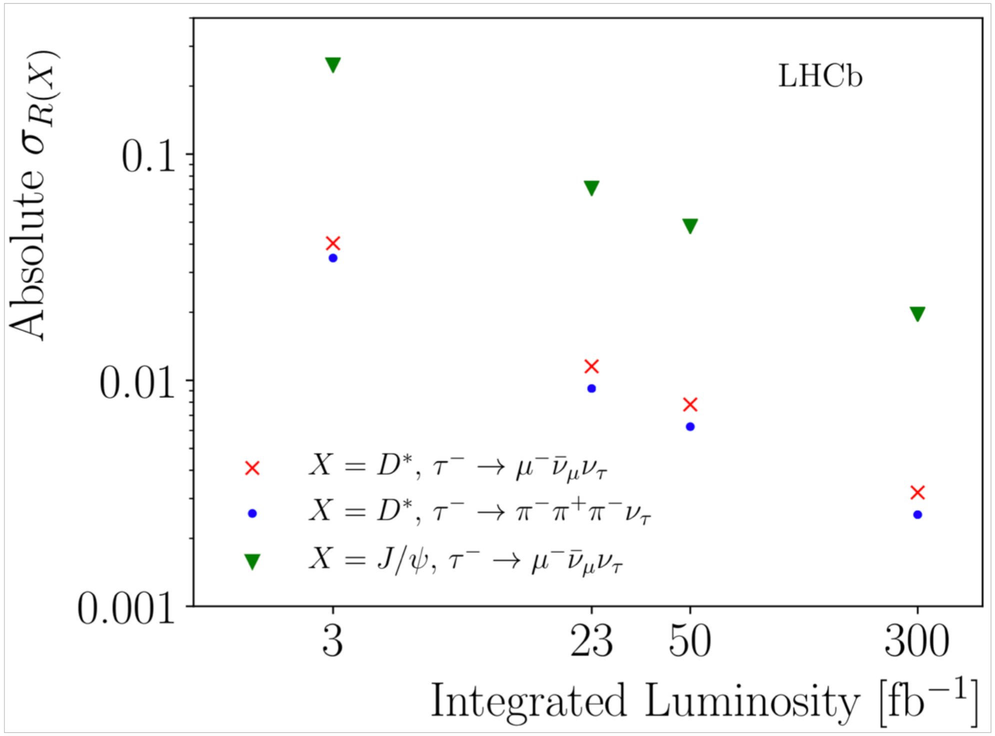




- New R(D)/R(D^*) combination BaBar/Belle/LHCb at 3.1σ from the SM.
- Previous combination at 3.8σ.
- Tension with SM reduced.

LHCb prospects on R(X_c)

- LHCb can perform measurements of LFU not accessible at Belle II:
  - R($\Lambda_c^{(*)}$), R(J/ψ), R($D_s^{(*)}$)
- Production fractions and efficiencies used to extrapolate the uncertainties.
- Precision in R(X_c) about 2-3% at the end of the Upgrade II.
- Sensitivity to angular observables need to be studied.



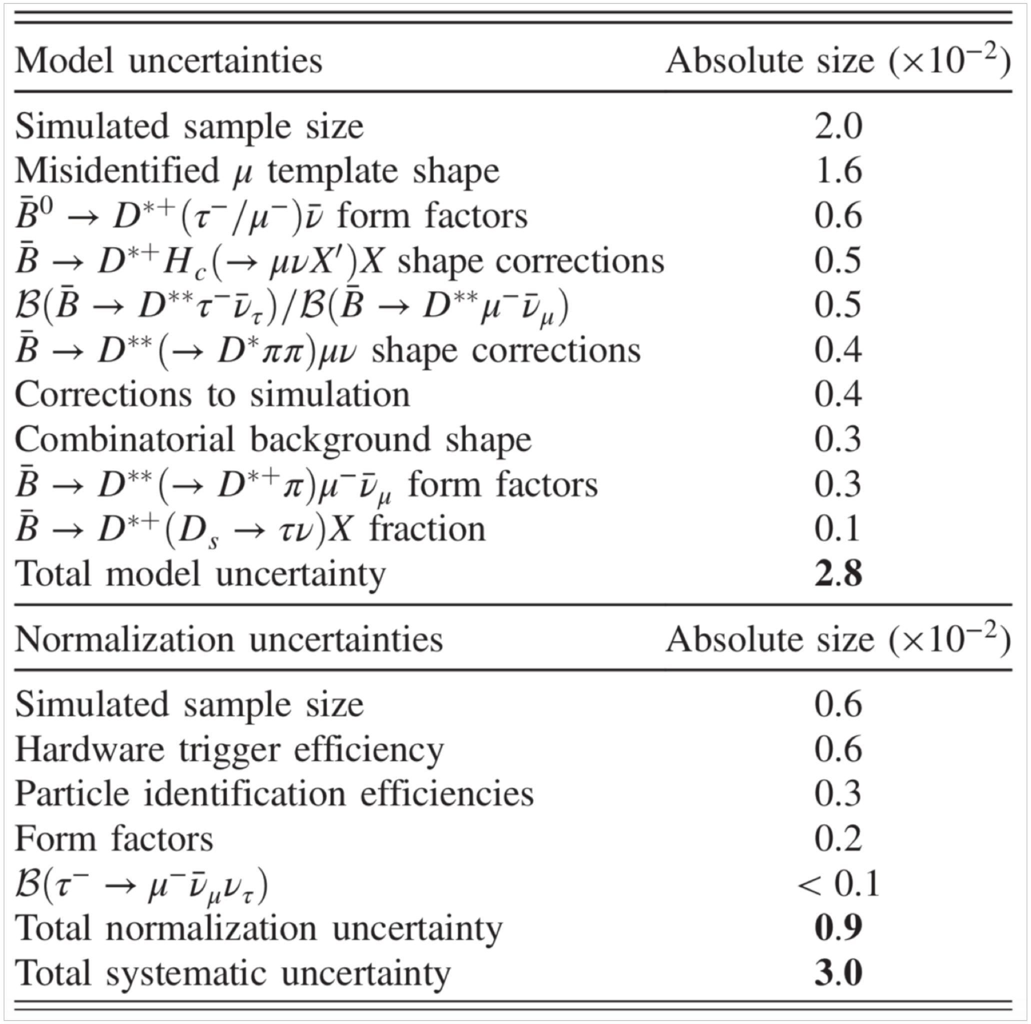
[arXiv:1808.08865]

Conclusions

- Study of semileptonic B decays at LHCb very challenging due to the missing neutrinos and no beam-energy constraint.
- Semileptonic b-hadron decays used to determine charmed baryons lifetimes.
- $|V_{ub}|/|V_{cb}|$ can be measured using channels and techniques complementary to those of B-factories.
- LHCb is able to perform measurements on semitauonic B decays using $\tau \longrightarrow \mu\nu\nu$ and $\tau^+ \longrightarrow \pi^-\pi^+\pi^-(\pi^0)\nu_\tau$ decays. Different systematics.
- $R(J/\psi)$ measured for the first time (first evidence of $B_c^+ \longrightarrow J/\psi\tau\nu$).
- Measurements of $R(\Lambda_c^{(*)})$, $R(J/\psi)$ and $R(D_s^{(*)})$ only possible at LHCb.
- LHCb aim to measure R(D) and $R(D^*)$ with 2-3% precision.

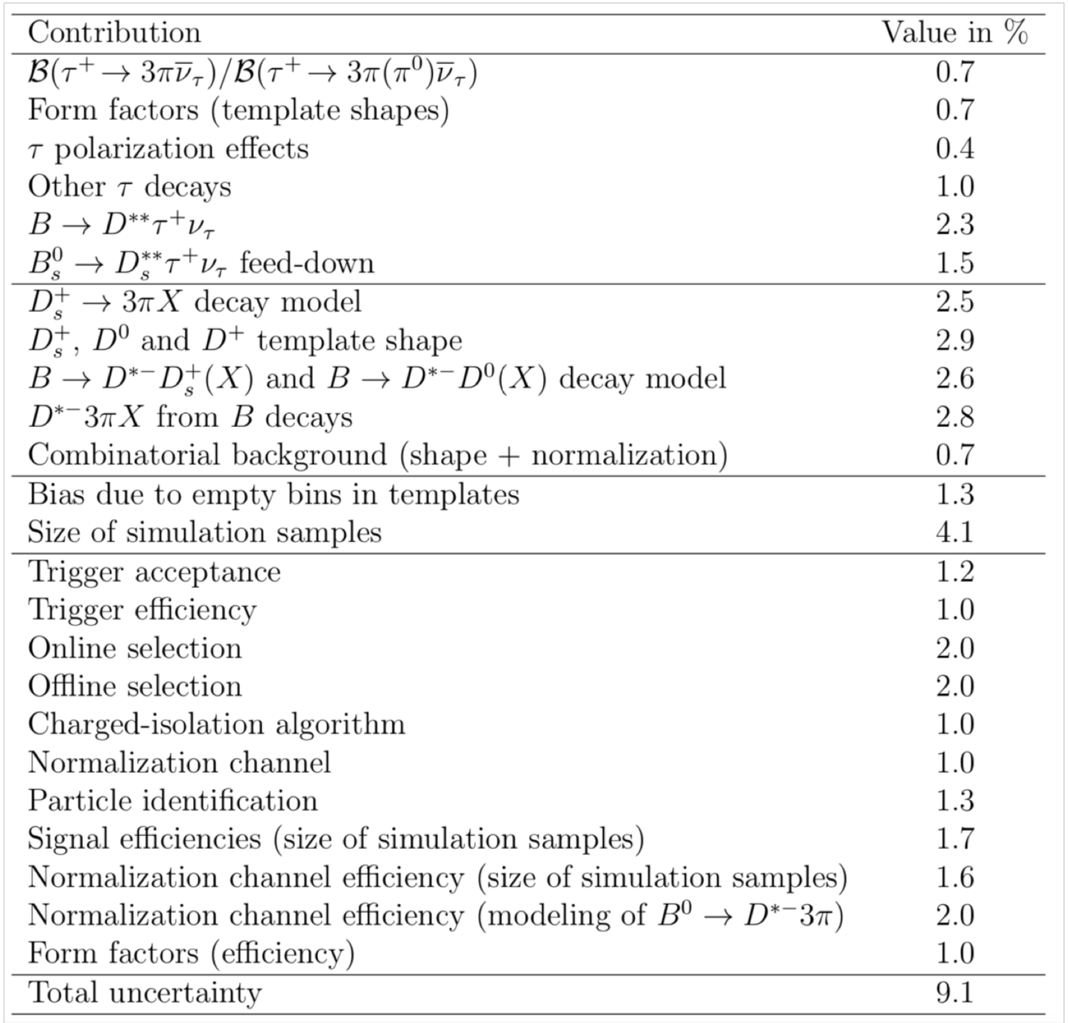
BACKUP

Systematics muonic R(D*)



Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\bar{B}^0 \to D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors	0.6
$\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{**}\mu^-\bar{\nu}_\mu)$	0.5
$\bar{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\bar{B} \to D^{**}(\to D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors	0.3
$\bar{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

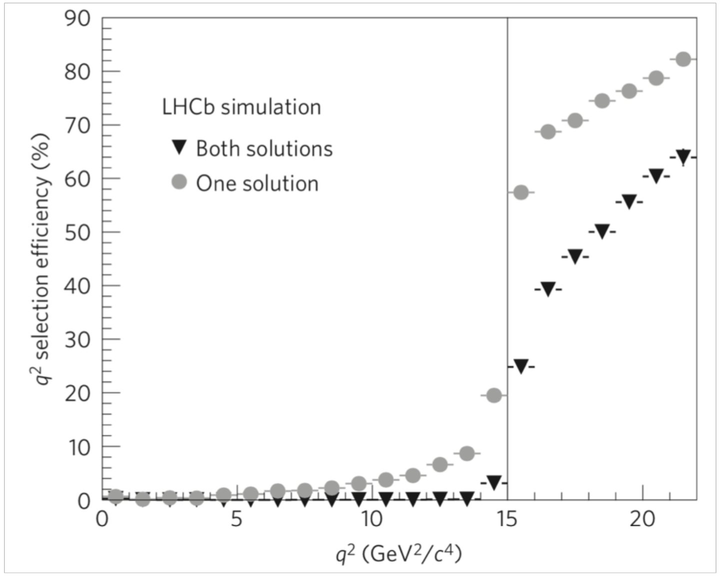
Systematics hadronic R(D*)



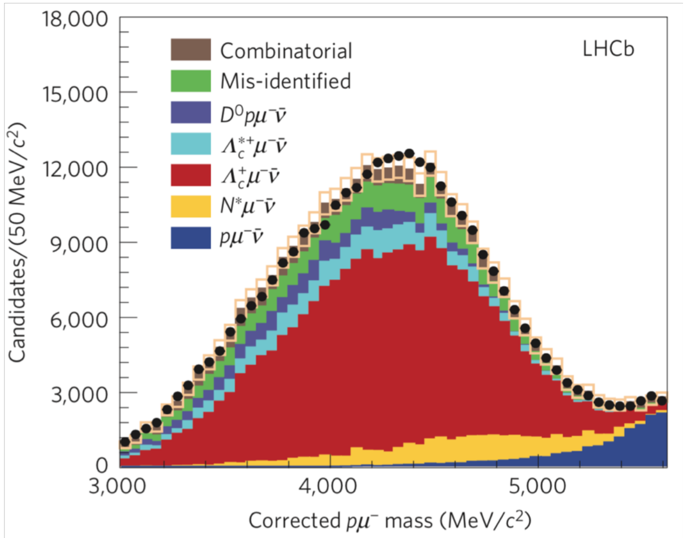
Contribution	Value in %
$\mathcal{B}(\tau^+ \to 3\pi\overline{\nu}_\tau)/\mathcal{B}(\tau^+ \to 3\pi(\pi^0)\overline{\nu}_\tau)$	0.7
Form factors (template shapes)	0.7
τ polarization effects	0.4
Other τ decays	1.0
$B \to D^{**}\tau^+\nu_\tau$	2.3
$B_s^0 \to D_s^{**}\tau^+\nu_\tau$ feed-down	1.5
$D_s^+ \to 3\pi X$ 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
Normalization channel	1.0
Particle identification	1.3
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
Form factors (efficiency)	1.0
Total uncertainty	9.1

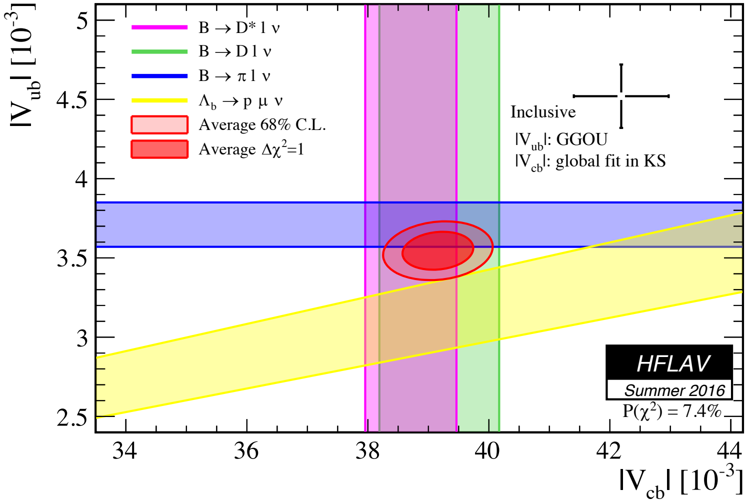
$|V_{ub}|/|V_{cb}|$ with $\Lambda_b^0 \longrightarrow p\mu^-\nu_\mu$

- Using the Λ_b^0 mass and direction of flight, **$q^2 = (p_{\Lambda b} - p_p)^2$** can be estimated **up to a two-fold ambiguity**.
- Events selected with **$q^2 > 7$ GeV²** ($p\mu\nu_\mu$) and **$q^2 > 15$ GeV²** ($\Lambda_c^+\mu\nu_\mu$) (both q^2 solutions above cut). Highest rate, best resolution (~1GeV²) and most precise Lattice calculations.



- Result: $$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\exp) \pm 0.004(lattice)$$





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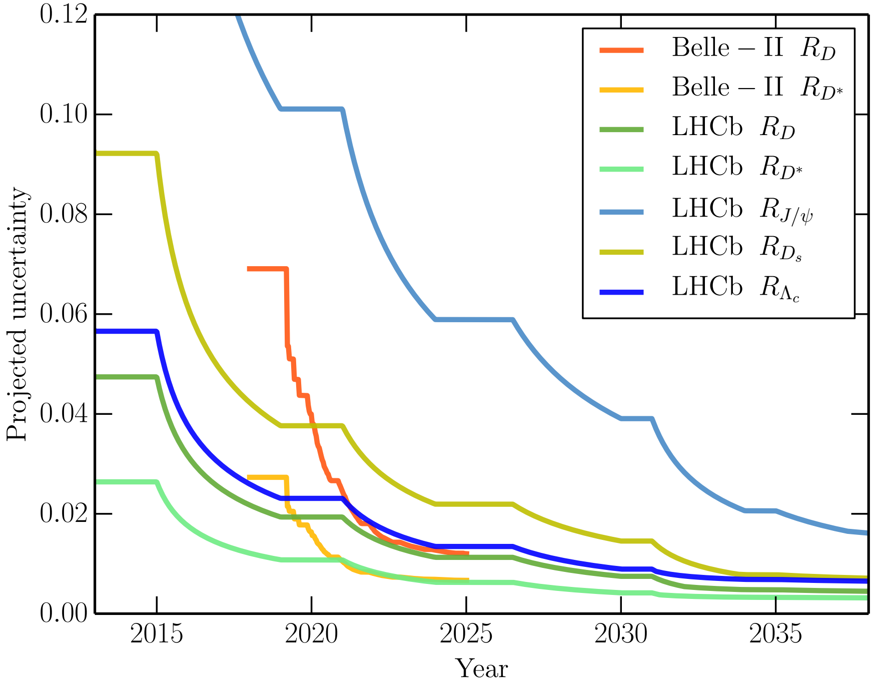
LHCb prospects on $R(X_c)$

- LHCb can perform measurements of LFU not accessible at Belle II:
  - $R(\Lambda_c^{(*)})$, $R(J/\psi)$, $R(D_s^{(*)})$
- Production fractions and efficiencies used to extrapolate the uncertainties.
- Precision in $R(X_c)$ about 2-3% at the end of the Upgrade II.
- Sensitivity to angular observables need to be studied.



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