Semitauonic B decays at LHCb

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on behalf of the LHCb collaboration

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anomalies about the LFU: what’s about?

- SM features Lepton Flavor Universality (LFU) \( \rightarrow \) the couplings of charged leptons to gauge bosons are lepton-flavour independent, and LFU is only broken by the Yukawa interaction, hence, \textit{any further deviation is a key signature of physics processes beyond the SM}

- \textbf{no evidence of deviation from the SM} in the precise (per-mil) tests of LFU in semi-leptonic \( K \) and \( \pi \) decays, purely leptonic decays, and in the electroweak precision observables
  - except for a 2.8 \( \sigma \) difference between the measurement of the branching fraction of the \( W \rightarrow \tau \nu_\tau \) decay with respect to \( W \rightarrow \mu \nu_\mu \) and \( W \rightarrow e \nu_e \) decays [Phys. Rept. 532 (2013) 119]

- \textbf{observed deviations from SM in B decays can naturally be grouped into two categories}
  - tree level semileptonic \( b \rightarrow c \tau \nu_\tau \) transitions \textit{this talk} (LHCb results)
  - FCNC \( b \rightarrow s l l \) transitions \textit{Alex Seuthe talk} (LHCb results)

- possible BSM scenarios: leptoquarks, new heavy vector bosons, \( H^\pm \) ...

- main test variables are ratios of decay rates
  - \textit{theoretically clean:} cancellation of QCD effects
  - \textit{experimentally clean:} cancellation of efficiency and reconstruction effects

14/02/19
detection of B semileptonic decays at LHCb


single-arm forward spectrometer
pseudorapidity range $2 < \eta < 5$

data samples

- 2010-11 $\sim 1.1$ fb$^{-1}$ at 7 TeV
- 2012 $\sim 2.1$ fb$^{-1}$ at 8 TeV
- 2015-18 $\sim 6$ fb$^{-1}$ at 13 TeV

data samples

- $\sim 25\%$ of $bb$-bar pairs in LHCb acceptance
- so far $> 10^{12}$ $bb$-bar pairs
- large boost $\rightarrow$ B mesons fly $\sim 1$ cm

precise tracking $\rightarrow$ excellent resolutions

- decay time resolution $\sim 45$ fs
- Impact Point resolution $\sim 20$ $\mu$m for high-$P_t$ tracks
- $\Delta p/p \sim 0.4\%$ at 5 GeV

excellent particle IDentification

- $\pi/K$ separation over 2-100 GeV, $\varepsilon_K \sim 90\%$ for $\sim 5\%$ ($\pi \rightarrow K$) misID
- powerful muon ID, $\varepsilon_\mu \sim 97\%$ for $1-3\%$ $\pi \rightarrow \mu$ misID
the next years @ LHCb

- upgrade installation started this January 2019 to be ready at the end of Long Shutdown 2 (LS2)
- restart data taking in 2021 at Run3
- higher instantaneous luminosity ➔ from $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ to $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$

more visible interactions per bunch crossing ➔ from 1 to about 5

- upgrade detector qualified to accumulate 50 fb$^{-1}$ at the end of Run4, LHCb-TDR{13,14,15,66}
- LS3: consolidation of the detector
- LS4: to take full advantage of the High Lumi-LHC, $\mathcal{L}$ up to 1-2 $\times 10^{34}$ cm$^{-2}$s$^{-1}$, the collaboration is proposing a major upgrade of the detector with the intent to collect 300 fb$^{-1}$ at the end of Run5, CERN/LHCC 2017-003, CERN/LHCC 2018-027
in this talk

\[ R(D^*) \text{ muonic: } B^0 \to D^*\ell^+\nu \text{ with } \tau \to \mu \nu_\mu \nu_\tau \]
\[ R(D^*) \text{ hadronic: } B^0 \to D^*\ell^+\nu \text{ with } \tau \to 3\pi(\pi^0)\nu_\tau \]
\[ R(J/\psi) \text{ muonic: } B^+_c \to J/\psi \ell^+\nu \text{ with } \tau \to \mu \nu_\mu \nu_\tau \]

- using \( D^+ \to D^0(\to K^+\pi^-) \pi^- \) and \( J/\psi \to \mu^+\mu^- \)

- complementary strategies \( \Rightarrow \) different backgrounds and systematics
- LHCb 2011 and 2012 data sample: **about 3 fb\(^{-1} \) at \( \sqrt{s} = 7, 8 \text{ TeV} \)**

**predictions:**

- \( R(D^*) = 0.258 \pm 0.005 \) uncertainties due to hadronic effects cancel to a large extent
  
- \( R(J/\psi) \subseteq [0.25, 0.28] \) the spread is due to the modeling of form factors
  

14/02/19
$R(D^*)$ with $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$
\[ R(D^*) \text{ with } \tau \rightarrow \mu \nu \bar{\nu}_\tau \]

\[ R(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)} \]

\[ \text{BR(}\tau \rightarrow \mu \nu \bar{\nu}_\tau\text{)} = (17.39 \pm 0.04)\% \]

**signal channel**

**normalization channel**

at LHCb

✓ B momentum unknown in production from pp collisions at LHC
✓ 3 missing neutrinos ➔ no narrow peak to fit
✓ large backgrounds from partially reco B decays: \( B \rightarrow D^{**} \mu \nu \), \( B \rightarrow (D \rightarrow X \mu)D^*X \)

➔ **MVA technique to reject physics backgrounds with additional charged tracks**
\( R(D^*) \) from \( \tau \rightarrow \mu \nu_\mu \bar{\nu}_\tau \)

at LHCb ➔

✓ statistics from high \( pp \rightarrow bb \) cross section at LHC
✓ use B flight direction to measure transverse component of missing momentum
✓ B boost along beam direction approximated with boost of the visible final state

\[ (p_B)_z = (m_B/m_{D^*\mu})(p_{D^*\mu})_z \]

✓ can then calculate rest frame quantities:

1. \( m^2_{\text{miss}} = (p_B - p_{D^*} - p_\mu)^2 \)
2. \( E^*_\mu \)
3. \( q^2 = (p_B - p_{D^*})^2 \)

\(~18\%\) resolution sufficient to retain discriminating power between signal and normalization channel

\( B \rightarrow D^* \tau \nu_\tau \)

\( B \rightarrow D^* \mu \nu_\mu \)

\[ LHCB \ [PRL\ 115\ (2015)\ 111803] \]
$R(D^*)$ from $\tau \rightarrow \mu \nu_\mu \bar{\nu}_\tau$

- Maximum likelihood fit to $m_{\text{miss}}^2$, $E^*_{\mu}$, $q^2$ distributions with 3D templates representing $B^0 \rightarrow D^* \tau \nu$, $B^0 \rightarrow D^* \mu \nu$, and background sources: $D^{**}$ feed-down, double charm, combinatorial, misidentified muons. Background and signal shapes extracted from control samples and simulations validated against data.

- Dominant component is $B^0 \rightarrow D^* \mu \nu$.
- $B^0 \rightarrow D^* \tau \nu$ component increases with $q^2$. 

LHCb [PRL 115 (2015) 111803]
**R(D*) from τ → µν_µ ¯ν_τ**

- Dominant systematic is due to the size of the simulation sample
- Systematic due to the modeling of the mis-ID µ template

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

1.9σ above Standard Model

\[ R(D^*)_\text{SM} = 0.258 \pm 0.003 \]

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**LHCb [PRL 115 (2015) 111803]**

**TABLE I. Systematic uncertainties in the extraction of \( R(D^*) \).**

<table>
<thead>
<tr>
<th>Model uncertainties</th>
<th>Absolute size ((\times 10^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>2.0</td>
</tr>
<tr>
<td>Misidentified µ template shape</td>
<td>1.6</td>
</tr>
<tr>
<td>( \bar{B}^0 \to D^{**}(\tau^-/\mu^-)\bar{\nu} ) form factors</td>
<td>0.6</td>
</tr>
<tr>
<td>( \bar{B} \to D^{*+}H_c(\to \mu\nu X)X ) shape corrections</td>
<td>0.5</td>
</tr>
<tr>
<td>( B(\bar{B} \to D^{<strong>}\tau^-\bar{\nu}_\tau)/B(\bar{B} \to D^{</strong>}\mu^-\bar{\nu}_\mu) )</td>
<td>0.5</td>
</tr>
<tr>
<td>( \bar{B} \to D^{**}(\to D^*\pi\pi)\mu\nu ) shape corrections</td>
<td>0.4</td>
</tr>
<tr>
<td>Corrections to simulation</td>
<td>0.4</td>
</tr>
<tr>
<td>Combinatorial background shape</td>
<td>0.3</td>
</tr>
<tr>
<td>( \bar{B} \to D^{<em>+}(\to D^{</em>+}\pi)\mu^-\bar{\nu}_\mu ) form factors</td>
<td>0.3</td>
</tr>
<tr>
<td>( \bar{B} \to D^{*+}(D_s \to \tau\nu)X ) fraction</td>
<td>0.1</td>
</tr>
<tr>
<td>Total model uncertainty</td>
<td>2.8</td>
</tr>
</tbody>
</table>

**Normalization uncertainties**

<table>
<thead>
<tr>
<th>Absolute size ((\times 10^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
</tr>
<tr>
<td>Hardware trigger efficiency</td>
</tr>
<tr>
<td>Particle identification efficiencies</td>
</tr>
<tr>
<td>Form factors</td>
</tr>
<tr>
<td>( B(\tau^- \to \mu^-\bar{\nu}<em>\mu\nu</em>\tau) )</td>
</tr>
<tr>
<td>Total normalization uncertainty</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
</tr>
</tbody>
</table>
$R(D^*)$ with $\tau^+ \rightarrow \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau$
$R(D^*)$ with $\tau \to 3\pi^\pm(\pi^0)\nu_\tau$

✓ BR($\tau \to 3\pi^\pm(\pi^0)\nu_\tau$) $\sim 13.9\%$ (was $\sim 17\%$ for the muonic case)
✓ no charged leptons in the final state $\Rightarrow$ no background from semileptonic decays
✓ the 3-prong topology enables the precise reconstruction of $\tau$ vertex
the requirement of a 3π vertex detached from B vertex suppresses $D^*$-$3\pi X$
background ($\sim 100 \times$ signal) improving S/B by factor $\sim 160$
R(D*) from $\tau \to 3\pi^\pm(\pi^0)\nu_\tau$

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- MVA technique to suppress the remaining backgrounds: double charm modes with non-negligible lifetime, $X_b \to D^*D_{(s)}(X)$ ($\sim 10 \times$ signal)
- exploits the resonant structures in the 3π systems from $\tau+$ and $D^+_s$ decays

LHCb [PRL 120 (2018) 171802]
LHCb [PRD 97 (2018) 072013]
$R(D^*)$ from $\tau \to 3\pi^{\pm}(\pi^0)\nu_{\tau}$

实验系统不确定性减少，通过将同一可观测终态的衰变进行归一化。

**visible final state:** $B^0 \to D^{*-}\pi^+\pi^-\pi^+$

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

**derive $R(D^*)$** by dividing by known semimuonic $B^0 \to D^*\mu\nu$ branching fraction

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

**measure**

- $B^0 \to D^*3\pi^\pm$ event yield, $N_{\text{norm}}$, from unbinned max likelihood fit to $m(D^*3\pi^\pm)$
- efficiencies from MC, validated using data control samples

**external inputs are**

$\mathcal{B}(B^0 \to D^*\mu\nu) = (4.88\pm0.10) \times 10^{-2}$

*HFLAV [arXiv:1612.07233]*

$\mathcal{B}(B^0 \to D^*3\pi) = (7.21\pm0.29) \times 10^{-3}$

*LHCb [PRD 87 (2013) 092001]*

$\mathcal{B}(\tau \to 3\pi(\pi^0)\nu_{\tau}) = (13.81\pm0.07)\%$

*PDG [Review of particle physics (2016)]*

$LHCb [PRL 120 (2018) 171802]$

$LHCb [PRD 97 (2018) 072013]$
signal yield from a 3D binned maximum likelihood fit to $q^2$, decay time, and BDT output background and signal shapes extracted from control samples and simulations validated against data

signal component increases with BDT output, while $D^*D_s^+X$ fraction decreases

dominant background at high BDT output $\rightarrow$ $D^*D^+X$ due to $D^+$ lifetime

$N(B^0 \rightarrow D^*\tau\nu) = 1296 \pm 86$

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

14/02/19
**R(D*) from \( \tau \to 3\pi^\pm(\pi^0)\nu_\tau \)**

- dominant systematic is due to the size of the simulation sample
- uncertainties on double charm backgrounds should improve with more data and improved external measurements
- uncertainty on efficiency ratio should improve with more statistics

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**TABLE I. Relative systematic uncertainties on \( R(D^{*-}) \).**

<table>
<thead>
<tr>
<th>Source</th>
<th>( \delta R(D^{<em>-})/R(D^{</em>-}) ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>4.7</td>
</tr>
<tr>
<td>Empty bins in templates</td>
<td>1.3</td>
</tr>
<tr>
<td>Signal decay model</td>
<td>1.8</td>
</tr>
<tr>
<td>( D^{<strong>}\tau\nu ) and ( D_s^{</strong>}\tau\nu ) feeddowns</td>
<td>2.7</td>
</tr>
<tr>
<td>( D_s^{+} \to 3\pi X ) decay model</td>
<td>2.5</td>
</tr>
<tr>
<td>( B \to D^{<em>-}D_s^+X, B \to D^{</em>-}D^+X, )</td>
<td>3.9</td>
</tr>
<tr>
<td>( B \to D^{*-}D^0X ) backgrounds</td>
<td></td>
</tr>
<tr>
<td>Combinatorial background</td>
<td>0.7</td>
</tr>
<tr>
<td>( B \to D^{*-}3\pi X ) background</td>
<td>2.8</td>
</tr>
<tr>
<td>Efficiency ratio</td>
<td>3.9</td>
</tr>
<tr>
<td>Normalization channel efficiency</td>
<td>2.0</td>
</tr>
<tr>
<td>(modeling of ( B^0 \to D^{*-}3\pi ))</td>
<td></td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>9.1</td>
</tr>
</tbody>
</table>

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

\(~ 0.9 \sigma \) above Standard Model

**compatible with the muonic channel**
$R(J/\psi)$ with $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$
signal decay chain with $\tau \rightarrow \mu\nu_\tau\nu_\mu$

$J/\psi \rightarrow \mu\mu$

signal channel

$B_c^+ \rightarrow J/\psi\tau^+\nu_\tau$

normalization channel

$B_c^+ \rightarrow J/\psi\mu^+\nu_\mu$

✓ signal and normalization decay chain with **identical visible final state** $\rightarrow (\mu\mu)\mu$

✓ **like in the muonic $R(D^*)$ analysis** $\rightarrow$
  1. use $m^2_{\text{miss}}, E^*(\text{unpaired muon}),$ and $q^2$ to disantagle between signal and normalization mode
  2. $B_c$ boost along beam direction approximated with boost of the visible system

✓ $B_c$ decay time (~ 3 times shorter than other $b$ hadrons) helps to discriminate the large background from lighter $b$ hadrons

✓ form factor parameters constrained experimentally using a data sample enriched in normalization decays

LHCb [PRL 120 (2018) 121801]
$R(J/\psi)$, LFU with $B_c$ decays

- Signal yield from a 3D binned maximum likelihood fit to
  - $m_{\text{miss}}^2$
  - $B_c$ decay time
  - $Z(E^*_\mu, q^2) \equiv$ flattened $4 \times 2$ histos of $E^*_\mu$ and $q^2$

- Background and signal shapes extracted from control samples and simulations validated against data

- Main backgrounds due to misidentified hadrons and combinatorial muons

- First evidence of the decay $B_c \rightarrow J/\psi \tau \nu_{\tau}$ ($3\sigma$)
R(J/ψ), LFU with B_c decays

- B_c^+ → J/ψ form factors
- size of the simulation sample second-largest systematic

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

~ 2. σ above Standard Model
summary
LFU tests at LHCb

LHCb has made 3 tests of LFU with semitauonic B decays so far

\[ R(D^*) \text{ (muonic)} = 0.336 \pm 0.027_{\text{stat}} \pm 0.030_{\text{syst}} \]

\[ R(D^*) \text{ (hadronic)} = 0.291 \pm 0.019_{\text{stat}} \pm 0.026_{\text{syst}} \pm 0.013_{\text{ext}} \]

\[ R(J/\psi) \text{ (muonic)} = 0.71 \pm 0.17_{\text{stat}} \pm 0.18_{\text{syst}} \]

**average** \( R(D^*) \), accounting for small correlations due to form factors, \( \tau \) polarization and \( D^{**}\tau^+\nu_\tau \) feed-down, **is 1.9 \( \sigma \) above SM**

\[ R(D^*) = 0.310 \pm 0.016_{\text{stat}} \pm 0.022_{\text{syst}} \]
world averages

between Belle, BaBar and LHCb we have 9 LFU tests done with semitaunic B decays so far

- $6 \times R(D^*)$, $2 \times R(D)$, $1 \times R(J/\psi)$
- all lie above SM expectations
- $R(D^*)$ average $3.0 \sigma$ from SM
world averages

\[ R(D) \text{ and } R(D^*) \text{ combination is about } 3.8 \sigma \text{ above the SM prediction} \]

\[ \text{reduction from } 4.1 \sigma \text{ due to increase in theory uncertainties} \]
conclusions and outlook

several deviations from LFU observed in ratios of semitauonic B decay rates ➔ while individually not that large, consistently shows a tension with the SM

✓ all ratios will be updated using the whole data sample collected so far, the main goal is to be competitive with the world average
✓ new analysis ongoing are:
  \[ R(D): B^+ \rightarrow D^0 \tau^+ \nu_\tau \]
  \[ R(D_s(*)): B_s \rightarrow D_s(*) \tau \nu_\tau \]
  \[ R(\Lambda_c(*)): \Lambda_b \rightarrow \Lambda_c(*) \tau \nu_\tau \]
  \[ R(p): \Lambda_b \rightarrow p \tau \nu_\tau \]
  ...
✓ \( \Lambda_b \rightarrow \Lambda_c \) form factor measurement \textit{LHCb [PRD 96 (2017) 112005]}

others are on the way: \( \Lambda_b \rightarrow \Lambda_c^*, B_s \rightarrow D_s(*) \)... 

looking for a fruitful competition/collaboration with BelleII

we are entering an exciting phase of precision measurements!

Thank you!
spares
detection of B semileptonic decays at LHCb


**single-arm forward spectrometer**

- pseudorapidity range $2 < \eta < 5$
- vertexing proper time resolution 30-50 fs
- tracking $\Delta p/p = 0.35 - 0.55\%$ $\sigma$(mass) = 10 - 25 MeV/c$^2$
- RICH KaonID $\varepsilon(K \rightarrow K) \approx 95\%$ misID rate ($\pi \rightarrow K$) $\approx 5\%$
- ECAL $\sigma(E)/E = 10\%/\sqrt{E} \oplus 1.\%$ $\text{HCal}$ $\sigma(E)/E = 69\%/\sqrt{E} \oplus 9\%$
- MuonID $\varepsilon(\mu \rightarrow \mu) \approx 97\%$ misID rate ($\pi \rightarrow \mu$) $= 1-3\%$

**data samples**

- 2010-11 $\sim 1.1\ fb^{-1}$ at 7 TeV
- 2012 $\sim 2.1\ fb^{-1}$ at 8 TeV
- 2015-18 $\sim 6.\ fb^{-1}$ at 13 TeV

- $\sim 25\%$ of $bb$-bar pairs in LHCb acceptance

- so far $> 10^{12}$ $bb$-bar pairs

- large boost $\rightarrow$

- $B$ mesons fly $\sim$1 cm
the LHCb trigger

- Fully optimised for flavour physics
- At first stage (L0) a hardware trigger fires on single hadrons, leptons and photons
- High Level Trigger (HLT): software application designed to reduce event rate from 1 M to \( \sim 10 \) k events/s, executed on a large computing cluster. Flexible design that can adapt to changing machine conditions and evolving physics programme
- Split HLT in two steps: buffer events to disk after HLT1 to perform online calibration & alignment
- HLT2 uses offline-quality calibration \( \rightarrow \) more discriminant trigger
- Offline-quality reconstruction up-front
the LHCb upgrade

- upgrade started this January 2019
- restart data taking in 2021 at $\mathcal{L}$ up to $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$
- upgrade detector qualified to accumulate 50 fb$^{-1}$

**upgrade all sub-detector electronics to 40 MHz readout**

**make all trigger decision in software and some new detectors**

**VELO** from microstrip sensors ($R,\phi$) to 55×55 $\mu$m$^2$ pixel sensors closer to the beam, from 5.5 mm to 3.5 mm

**Upstream Tracker** silicon strip detector
- adapt segmentation to increased occupancy

**SciFi Tracker** 3 stations of X-U-V-X scintillating fibre planes

**PID** new photodetectors for RICH1 and RICH2

**Calorimetry** new readout electronics

**Muon System** new readout electronics

⇒ *less than 10% of all channels will be kept*

LHCb-TDR-\{13,14,15,66\}
R(D*) from \( \tau \rightarrow 3\pi^\pm(\pi^0)\nu_\tau \)

✓ MVA technique to suppress the remaining backgrounds: double charm modes with non-negligible lifetime, \( X_b \rightarrow D^* D_{(s)}(X) \) (\( \sim 10 \times \) signal) \( \Rightarrow \) exploits the resonant structures in the \( 3\pi \) systems from \( \tau^+ \) and \( D^{+s} \) decays

✓ data control samples of \( D^* D^{+s} X, D^* D^+ X \) and \( D^* D^0 X \) used to correct simulation
outlook for $R(D^*)$ and $R(J/\psi)$

*Physics case for LHCb Upgrade II*  *arXiv:1808.08865 (2018)*

- All results based on **3/fb** at 7-8TeV  (Run 1 2010-2012)
  - $\sigma(R_{D^*})$: 0.027
  - $\sigma(R_{J/\psi})$: 0.17 (stat)

- We have another **6/fb** at 13TeV (Run 2 2015-2018)
  - $\times 4$ in B statistics due to increased production $X$-section
  - $\sigma(R_{D^*})$: 0.030
  - $\sigma(R_{J/\psi})$: 0.18 (syst)

- LHCb upgrade during shutdown (2019-2020)
  - 40MHz readout and trigger entirely in software
  - Better vertexing for reducing backgrounds to $\tau$, $D$ and $B$
  - After upgrade can reduce syst errors

- Integrated luminosity **50/fb** in Runs 3 & 4
  - Higher instantaneous luminosity $2\times10^{33}$/cm$^2$/s
  - $\sigma(R_{D^*})$: 0.007
  - $\sigma(R_{J/\psi})$: 0.07

- Possible major upgrade in $\sim$2030
  - Much higher luminosity $2\times10^{34}$, with target of **300/fb**
  - $\sigma(R_{D^*})$: 0.002
  - $\sigma(R_{J/\psi})$: 0.02
  - similar to $\sigma$(SM)
\[ \Lambda_b \rightarrow \Lambda_c \mu \nu \] form factors

- differential distributions are crucial for comparisons with HQET and lattice QCD, also a first step towards measuring \( |V_{cb}| \)
- the decay \( \Lambda_b \rightarrow \Lambda_c \mu \nu \) is described by 6 form factors, reducing to a single function in heavy quark limit \( \Rightarrow \) the Isgur-Wise function \( \xi_B(w) \):

\[
\frac{d\Gamma}{dw} = GK(w)\xi_B^2(w) \quad w = v_{\Lambda_b} \cdot v_{\Lambda_c} = \frac{m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2}{2m_{\Lambda_b}m_{\Lambda_c}}
\]

- expanding \( \xi_B(w) \) around \( w=1 \) yields:

\[
\xi_B(w) = 1 - \rho^2(w-1) + \frac{1}{2}\sigma(w-1)^2 + \ldots
\]

used for fitting the decay rate

- large and clean samples of \( \Lambda_b \rightarrow \Lambda_c \mu \nu \) decays: \( 2.7 \times 10^6 \) in analyses Run1 sample

- subtract feed-down from higher resonances \( \Lambda_c(2595) \), \( \Lambda_c(2625) \), \( \Lambda_c(2765) \), \( \Lambda_c(2880) \)
$\Lambda_b \to \Lambda_c \mu \nu$ form factors

- $w$ distributions are unfolded and corrected for efficiencies
- then they are fit using 3 approaches, here is example from Taylor expansion $\Rightarrow$ they are in good agreement with HQET predictions

- also comparison with $d\Gamma/dq^2$ distributions with lattice QCD shows excellent agreement
  
  [PRD92 (2015) 034503]