Lepton universality tests with tree-level semileptonic decays

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DESY colloquium
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\( \chi^2 = 1.0 \) contours

\( R(D) = 0.300(8) \) HPQCD (2015)

\( R(D) = 0.299(11) \) FNAL/MILC (2015)

\( R(D^*) = 0.252(3) \) S. Fajfer et al. (2012)

Average

BaBar, PR 109, 101802 (2012)

Belle, PRD 92, 072014 (2015)

LHCb, PR 115, 111803 (2015)

Belle, PRD 94, 072007 (2016)

Belle, PRL 118, 211801 (2017)

LHCb, FPCP 2017

HFLAV

FPCP 2017

\( P(\chi^2) = 71.6\% \)

\( P(D) = 0.65 \) CMS (2015)

\( P(D) = 0.62 \) ATLAS (2015)

\( P(D) = 0.60 \) Belle (2016)

\( P(D) = 0.58 \) BaBar (2012)

\( P(D) = 0.55 \) LHCb (2015)

\( P(D) = 0.53 \) CMS (2015)

\( P(D) = 0.50 \) ATLAS (2015)

\( P(D) = 0.47 \) Belle (2016)

\( P(D) = 0.45 \) BaBar (2012)

\( P(D) = 0.43 \) LHCb (2015)

\( P(D) = 0.40 \) CMS (2015)

\( P(D) = 0.38 \) ATLAS (2015)

\( P(D) = 0.35 \) Belle (2016)

\( P(D) = 0.33 \) BaBar (2012)

\( P(D) = 0.30 \) LHCb (2015)

\( P(D) = 0.28 \) CMS (2015)

\( P(D) = 0.26 \) ATLAS (2015)

\( P(D) = 0.24 \) Belle (2016)

\( P(D) = 0.22 \) BaBar (2012)

\( P(D) = 0.20 \) LHCb (2015)

\( P(D) = 0.18 \) CMS (2015)

\( P(D) = 0.16 \) ATLAS (2015)

\( P(D) = 0.14 \) Belle (2016)

\( P(D) = 0.12 \) BaBar (2012)

\( P(D) = 0.10 \) LHCb (2015)

\( P(D) = 0.08 \) CMS (2015)

\( P(D) = 0.06 \) ATLAS (2015)

\( P(D) = 0.04 \) Belle (2016)

\( P(D) = 0.02 \) BaBar (2012)

\( P(D) = 0.00 \) LHCb (2015)
1. Introduction to B physics and LHCb

2. LHCb tests of Lepton Universality in tree decays

3. Future prospects
Searching for new physics beyond the SM

Direct: Sensitivity to heavier BSM scales requires higher energy

Indirect: Sensitivity to heavier BSM scales requires higher precision
Indirect example

\[ m_n \sim 1 \text{ GeV} \]
Indirect example

\[
m_n \sim 1 \text{ GeV} \quad \text{and} \quad m_w \sim 100 \text{ GeV}
\]

Amplitude \( \propto \frac{g^2}{m_w^2} \)
How to see…

…a measurable effect of a tiny BSM amplitude that is inversely proportional to the BSM mass scale?

Focus on processes/observables for which

• SM contribution is suppressed,
• and can be precisely computed.
• Experiments can reach high precision.
Quark flavour mixing

\[ V_{\text{CKM}} \approx \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]

\( V_{\text{CKM}} \) is hierarchical \( \Rightarrow \) SM amplitudes suppressed.

\( (V_{\text{CKM}} \) is also the sole source of CPV in the SM*)

\( V_{\text{CKM}} \) must be unitary \( \Rightarrow \) testability.

*For SM with \( \theta_{QCD} = m_v = 0 \)
Quark flavour mixing

$V_{\text{CKM}} \approx$

$V_{\text{CKM}}$ is hierarchical $\Rightarrow$ SM amplitudes suppressed.

($V_{\text{CKM}}$ is also the sole source of CPV in the SM*)

$V_{\text{CKM}}$ must be unitary $\Rightarrow$ testability.

*For SM with $\theta_{\text{QCD}} = m_V = 0$
Quark flavour mixing

$V_{\text{CKM}}$ is hierarchical $\Rightarrow$ SM amplitudes suppressed. ($V_{\text{CKM}}$ is also the sole source of CPV in the SM*)

$V_{\text{CKM}}$ must be unitary $\Rightarrow$ testability.

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

*For SM with $\theta_{\text{QCD}} = m_\nu = 0$
The SM CKM mechanism is the leading source of quark flavour mixing.

We are nowhere near exhausting the potential BSM sensitivity of quark flavour.
BaBar and Belle

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$

BaBar 1999-2008
~500 million BB

Belle 1999-2010
~800 million BB

Later I will mention Belle-II, which will collect ~50x more luminosity during 2018-2024.
The LHC
The LHC
The LHC
Current dataset $\sim 10^{12}$ b hadrons
Lepton universality in the SM

Couplings of above vertices are invariant under exchange of lepton generation.

Tested in W and Z decays at LEP, Kaon and pion decays, τ and μ lifetimes…
LU tests with b decays

Tree

\[ R(D^{(*)}) \]  
\[ \tau \text{ versus } \mu, e \text{ ratios} \]

Loop

\[ R(K^{(*)}) \]  
\[ \mu\mu \text{ versus } ee \text{ ratios} \]
LU tests with $b$ decays

Tree

$R(D^{(*)})$

$\tau$ versus $\mu, e$ ratios

Focus of my talk

Loop

$R(K^{(*)})$

$\mu\mu$ versus $ee$ ratios

Covered in recent DESY colloquium
by Johannes Albrecht
Jargon buster — $D^*$

$D^{+,0}$ mesons — spin 0
Jargon buster — $D^*$

$D^{+,0}$ mesons — spin 0

$D^{*+,0}$ mesons — spin 1 excitation

$D^*(2010)^\pm$

$I(J^P) = 1/2(1^-)$

<table>
<thead>
<tr>
<th>Fraction ($\Gamma_i / \Gamma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \pi^+$</td>
</tr>
<tr>
<td>$D^+ \pi^0$</td>
</tr>
<tr>
<td>$D^+ \gamma$</td>
</tr>
</tbody>
</table>
Jargon buster — $D^*$

![Diagram of particle interactions involving $D^*$, $D^0$, $K^-$, $\pi^+$, and $\pi^+$]

![Graph showing events vs. $m(D^0\pi_s)$ with data points, fit, and background indicated]

$LHCb (a)$

- **Data**
- **Fit**
- **Background**

Events / $(0.05 \text{ MeV/c})$

$m(D^0\pi_s)$ [MeV/c$^2$]

$\Delta/\sigma$
$R(D^{(*)})$

\[
R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)} \tau \nu)}{\mathcal{B}(B \rightarrow D^{(*)} \mu \nu)}
\]

SM predictions:

$R(D) = 0.300 \pm 0.008$

$R(D^*) = 0.252 \pm 0.003$
$R(D^{(*)})$ in SM and beyond
$R(D^{(*)})$ in SM and beyond
$R(D^{(*)})$ in SM and beyond
$R(D^{(*)})$ in SM and beyond
$R(D^{(*)})$ at B factories

Not a rare decay

$\text{BR}(B \rightarrow D^* \tau \nu) \sim 1\%$

The problem is the background...
$R(D^{(*)})$ at B factories

If only we knew the momentum of the B…

Tagging efficiency
~ few x $10^{-3}$ for full reconstruction
~ $10^{-2}$ for semileptonic tag
(Example fit projection)

$D^{*+} \ell$

$D^{*+} \ell$

$\overline{B} \rightarrow D \ell^- \bar{\nu}_\ell$

$\overline{B} \rightarrow D^* \ell^- \bar{\nu}_\ell$

$\overline{B} \rightarrow D^{**}(\ell^- / \tau^-) \bar{\nu}$

Background

$\overline{B} \rightarrow D^* \tau^- \bar{\nu}_\tau$
BaBar 2012

$R(D^*) \ 2.7 \sigma$ above SM
$R(D) \ 2.0 \sigma$ above
Combination $3.4 \sigma$ away
Recent Belle analysis with $\tau \to \pi (\pi^0) \nu$  

First $\tau$ polarisation measurement!
Possible at LHCb?
In pp collisions the rest of the event doesn’t provide any useful kinematic constraint. Different approaches required.
$R(D^*)$ from LHCb

Muonic $\tau$ decay (18%)

Hadronic $\tau$ decay (15%)

PRL 115, 111803 (2015)

$\tau$ BR = (17.39 ± 0.04)%

1708.08856v2 (2017)

1711.02505 (2018)

$\tau$ BR* = (14.55 ± 0.06)%
Muonic $R(D^*)$ from LHCb

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

(Normalisation and background)

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)}{\mathcal{B}(B \rightarrow D^{(*)}\mu\nu)}$$
Muonic $R(D^*)$ from LHCb

(Normalisation and background)
Muonic $R(D^*)$ from LHCb

Below we assume knowledge of the $b$ momentum!

Try the approximation $(\gamma \beta Z)_B = (\gamma \beta Z)_{\text{visible}}$?

And exploit the measured $B$ flight trajectory.

![Graphs showing $m_{miss}^2$, $E_{mu}$, and $q^2$ distributions.](image)
Muonic $R(D^*)$ from LHCb
Other backgrounds

Data

- $B \rightarrow D^* \tau \nu$
- $B \rightarrow D^* H_c \ (\rightarrow l \nu X')X$
- $B \rightarrow D^{**} l \nu$
- $B \rightarrow D^* \mu \nu$

Combinatoric

Misidentified $\mu$
Double charm

- Data
- \( B \rightarrow D^* \tau \nu \)
- \( B \rightarrow D^* H_c (\rightarrow \nu X') X \)
- \( B \rightarrow D^{**} \nu \)
- \( B \rightarrow D^* \mu \nu \)
- Combinatoric
- Misidentified \( \mu \)
Double charm

“Anti-isolation”
Control region

Data
- $B \to D^*\tau\nu$
- $B \to D^*H_c (\to l\nu X')X$
- $B \to D^{**}\nu$
- $B \to D^*\mu\nu$
- Combinatorial
- Misidentified $\mu$

E.g. identified kaon

Candidates / (0.3 GeV$^2$/c$^4$)

$m_{miss}^2$ (GeV$^2$/c$^4$)
4 coarse $q^2$ bins, and finer bins in $m^2_{\text{miss}}$, $E_\mu$.

Projection of $m^2_{\text{miss}}$ in the highest purity $q^2$ bin:
LHCb muonic $R(D^*)$ result

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

Consistent with BaBar and Belle results

2.1σ above the SM prediction
First LHCb analysis with $B_c$ decays

\[ \mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} \]

SM predictions for $R(J/\psi)$ lie in the range 0.25–0.28.
First LHCb analysis with $B_c$ decays

👍 Short $B_c$ lifetime

👎 No flying charm hadron
$R(J/\Psi)$ fit and results

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

Higher than the predictions, but within 2$\sigma$
LHCb $R(D^*)$ with $\tau \to \pi\pi\pi(\pi^0)\nu$

👍 No $b \to c\mu\nu X$ background

👍 Mass peaks in the backgrounds

👍 Only one $\nu$ from $\tau$ decay vertex
LHCb $R(D^*)$ with $\tau \to \pi\pi\pi(\pi^0)\nu$
The *prompt* background

\[ \mathcal{B}^\circ \rightarrow b \bar{c} \rightarrow u \bar{d} \pi\pi, \ldots \]

\[ B/S \sim 10^2 \]
The *prompt* background

\[ B/S \sim 10^2 \]
The *prompt* background

\[ B/S \sim 10^2 \]
The prompt background
Detached vertex method
Double charm background

\[ BR(D_s \rightarrow 3\pi X) \sim 25\% \]

\[ B/S \sim 10 \]

\( D_s \rightarrow 3\pi X \) dominated by various modes with intermediate \( \eta(\prime), \omega, \rho, \) etc…

Some measured, some not…

Also contributions with \( D^*D^+X, D^*D^0X \)…
The anti-double-charm BDT

Kinematics, E.g.

Neutral isolation

LHCb simulation

Signal
Background

Candidates / (59.5 MeV/c²)

max [m(π⁻ π⁺)] [MeV/c²]

LHCb

Candidates / (20 MeV/c²)

m(D⁻ π⁺ π⁺) [MeV/c²]

LHCb

All

With energy in ECAL > 8 GeV
The anti-double-charm BDT
$D_s$ enriched control region
Controlling the double-charm

$D_s, D^*_s, \text{ etc.}$

$D_{s+} \rightarrow \pi^+ \pi^- \pi^+$
Controlling the double-charm

\[ B^0 \rightarrow D^*-D_{s}^+ \]

\[ B^0 \rightarrow D^*-D_{s}^{*+} \]

\[ B^0 \rightarrow D^*-D_{s} l^+ \]

\[ B^0 \rightarrow D^{**}-D_{s}^+ X \]
Normalisation

Actually measure

\[
\frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_{\tau})}{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi)}
\]

And use external measurements of \( B(B \rightarrow D^{*} 3\pi) \) and \( B(B \rightarrow D^{*} \mu\nu) \) to get \( R(D^*) \).

Benefit from a new (2016) measurement of \( B(B \rightarrow D^{*} 3\pi) \) from BaBar. \textit{PRD} 94 (2016) 091101

\[
B(B \rightarrow D^{*} 3\pi) = (0.726 \pm 0.011 \pm 0.031)\%
\]
Normalisation

Actually measure

\[ \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)} \]

\( LHCb \)

\(~20k\) signal
The signal fit

Higher BDT score

$D^*\tau_N$
$D^{**}\tau_N$
$D^*DsX$
$D^*D+X$
$D^*3\pi X$
$D^*D0X$
comb. bkg

τ decay time (ns)  $q^2$ (GeV$^2$/c$^4$)
The result

\[ B(D^*\tau\nu)/B(3D^*\pi) = 1.93 \pm 0.13_{\text{stat}} \pm 0.17_{\text{syst}} \]

\[ R(D^*) = 0.285 \pm 0.019_{\text{stat}} \pm 0.025_{\text{syst}} \pm 0.014_{\text{ext}} \]

Consistent with the SM and with the previous results
The state-of-the-art

\[ R(D) = 0.300(8) \text{ HPQCD (2015)} \]
\[ R(D) = 0.299(11) \text{ FNAL/MILC (2015)} \]
\[ R(D^*) = 0.252(3) \text{ S. Fajfer et al. (2012)} \]

HFLAV FPCP 2017 \( P(\chi^2) = 71.6\% \)

The tension is now at the level of 4.1 \( \sigma \)
Further 2 fb\(^{-1}\) is anticipated in 2018.

Given higher cross sections, and trigger improvements, Run-II typically represents a 4-5x increase over Run-I!
LHCb in the near future

\[ R_{\tau \mu} \] measurements in progress with

**b → c**

- \(B \rightarrow D^{*+}\tau\nu\)
- \(B \rightarrow D^{+0}\tau\nu\)
- \(B_s \rightarrow D_s\tau\nu\)
- \(\Lambda_b \rightarrow \Lambda^{(*)}\tau\nu\)
- \(B_c \rightarrow J/\psi\tau\nu\)
- etc...

**b → u**

- \(\Lambda_b \rightarrow \rho\tau\nu\)
- \(B \rightarrow \rho\rho\tau\nu\)
- etc..

**B hadron**

- \(b\)
- \(u,d,s,c\)

**\(\bar{B}\) hadron**

- \(\bar{b}\)
- \(\bar{u},\bar{d},\bar{s},\bar{c}\)
SuperKEKB and Belle II

Aim to record ~50x Belle dataset by 2025!
LHCb upgrades

- Upgrade I (50 fb⁻¹)
  Full software trigger
  (5x) increase in luminosity to 2x10^{33} cm⁻²s⁻¹.

- Upgrade II (300+ fb⁻¹)
  Increase luminosity to 1—2 x 10^{34} cm⁻²s⁻¹.
  Fast-timing, higher granularity and rad-hardness.
Summary

Do we see breaking of lepton universality in b decays?

Too early to claim any discovery, but exciting prospects from LHCb and Belle II!
Backup slides start here
\( R(D^*) \) muonic systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>( \sim \delta R_{D}/R_{D} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Template stats</td>
<td>6%</td>
</tr>
<tr>
<td>Background muon mis-ID</td>
<td>5%</td>
</tr>
<tr>
<td>Form factors</td>
<td>3%</td>
</tr>
<tr>
<td>Relative efficiency</td>
<td>3%</td>
</tr>
<tr>
<td>Background (( DD_s ))</td>
<td>1.5%</td>
</tr>
<tr>
<td>Background (combinatoric)</td>
<td>1%</td>
</tr>
<tr>
<td>Total</td>
<td>9%</td>
</tr>
</tbody>
</table>
Other double-charm

$D^0 \rightarrow 3\pi X$ rate constrained w.r.t. Clean $D^0 \rightarrow K3\pi$ which has well known BR.

Can’t apply same approach to $D^+$ since relevant BRs aren’t well known. More freedom in our final fit.
$D_s$ enriched region
FIG. 4. The SM predictions for $R(D)$ and $R(D^*)$, imposing (left) or not imposing (right) the QCDSR constraints (see Table IV). Gray ellipses show other SM predictions (last three rows of Table IV). The black ellipse shows the world average of the data [9]. The contours are 68% CL ($\Delta \chi^2 = 2.3$), hence the nearly $4\sigma$ tension.
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Method</th>
<th>N evts $\mathrm{B^0 \rightarrow D^*\tau\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BABAR</td>
<td>Leptonic_hadronic tag</td>
<td>$245 \pm 27$</td>
</tr>
<tr>
<td>BELLE</td>
<td>Leptonic hadronic tag</td>
<td>$0.4 \times 500 = 200$</td>
</tr>
<tr>
<td>BELLE</td>
<td>Single pi hadronic tag</td>
<td>$88 \pm 11$</td>
</tr>
<tr>
<td>LHCb</td>
<td>3$\pi$ Hadronic</td>
<td>$1273 \pm 95$</td>
</tr>
</tbody>
</table>
Table 1: Systematic uncertainties in the determination of $R(J/\psi)$.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Size ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limited size of simulation samples</td>
<td>8.0</td>
</tr>
<tr>
<td>$B_c^+ \to J/\psi$ form factors</td>
<td>12.1</td>
</tr>
<tr>
<td>$B_c^+ \to \psi(2S)$ form factors</td>
<td>3.2</td>
</tr>
<tr>
<td>Fit bias correction</td>
<td>5.4</td>
</tr>
<tr>
<td>$Z$ binning strategy</td>
<td>5.6</td>
</tr>
<tr>
<td>Misidentification background strategy</td>
<td>5.6</td>
</tr>
<tr>
<td>Combinatorial background cocktail</td>
<td>4.5</td>
</tr>
<tr>
<td>Combinatorial $J/\psi$ sideband scaling</td>
<td>0.9</td>
</tr>
<tr>
<td>$B_c^+ \to J/\psi H_cX$ contribution</td>
<td>3.6</td>
</tr>
<tr>
<td>Semitauonic $\psi(2S)$ and $\chi_c$ feed-down</td>
<td>0.9</td>
</tr>
<tr>
<td>Weighting of simulation samples</td>
<td>1.6</td>
</tr>
<tr>
<td>Efficiency ratio</td>
<td>0.6</td>
</tr>
<tr>
<td>$\mathcal{B}(\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau)$</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td><strong>17.7</strong></td>
</tr>
<tr>
<td><strong>Statistical uncertainty</strong></td>
<td><strong>17.3</strong></td>
</tr>
</tbody>
</table>
New result has highest statistical precision.

Naive $R(D^*)$ average is $3.4\sigma$ above SM.

Naive $R(D,D^*)$ average is $4.1\sigma$ above SM...
\[ \frac{d\Gamma^{SM}(\bar{B} \to D^{(*)} \ell^- \bar{\nu}_\ell)}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |p^*_{D^{(*)}}| q^2}{96\pi^3 m_B^2} \left( 1 - \frac{m_{\ell}^2}{q^2} \right)^2 \] 

universal and phase space factors

\[ \times \left[ \left( |H_+|^2 + |H_-|^2 + |H_0|^2 \right) \left( 1 + \frac{m_{\ell}^2}{2q^2} \right) + \frac{3m_{\ell}^2}{2q^2} |H_s|^2 \right] \] 

hadronic effects

(3)
Naive NP scale

$\sim 30\%$ effect in $\tau/\mu$ versus SM

$\left(\frac{g}{m_W}\right)^2 V_{cb} \sim \sqrt{30\%} \left(\frac{g}{m_W}\right)^2 |V_{cb}|^2$

$\left(\frac{g_{NP}}{\Lambda}\right)^2 \sim \left(\frac{g_{NP}}{3 \text{ TeV}}\right)^2$