Lepton Flavour Universality Tests at LHCb

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Lepton Flavour Universality

In the SM, leptons from different families have the same coupling to $W$ and $Z$ bosons.

It is possible to probe the effective couplings in decays of $B$ hadrons in different tree level and FCNC processes.

Measurements using ratios of $B$ decays cancel many of the theoretical uncertainties.

This talk will cover LFU studies in LHCb using $3\text{fb}^{-1}$ @ 7/8 TeV

+ NP Contributions?
LHCb Detector

Excellent vertex resolution

$IP_x$ Resolution: $13\mu m$

Decay Time: $\sim50fs$

Excellent tracking and momentum resolution.

Excellent particle identification capabilities.
LHCb Detector

Excellent vertex resolution

Excellent tracking and momentum resolution.
\[ \Delta p/p \sim 0.4 - 0.6\% \]

Excellent particle identification capabilities.

RICH K-\(\pi\)-p ID
99% efficiency \(\mu\) ID
Calo e-gamma ID
LHCb Detector

Excellent vertex resolution

Excellent tracking and momentum resolution.

Excellent particle identification capabilities.

~7 fb⁻¹ of data so far!

LFU in Tree Level Processes
\[ R(J/\psi) = \frac{B(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{B(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} \]

Identical Reconstructed Final state: \( \mu^+ \mu^- \mu^+ \)

Main Backgrounds:
- \( B \rightarrow J/\psi \ h; \ h \) misID as \( \mu \)
- \( B_c \rightarrow J/\psi \ D(\mu \nu \ X) \ X \)
- \( J/\psi \ \mu \) Combinatorial Bkg

Analysis using 3fb\(^{-1}\) Run 1 data

SM Prediction for \( R(J/\psi) \): 0.25 - 0.28 (ref in backup)
In order to calculate signal yield a template fit is used.

Simultaneous fit in $m_{\text{miss}}^2$, $B_c$ lifetime and $Z(E_\mu, q^2)$

$Z$ is a categorical variable separating candidates in bins of $E_\mu$ and $q^2$

Tau decay $m_{\text{miss}}^2$ softer due to 3 missing neutrinos compared to 1 in the $\mu$ case.
In order to calculate signal yield a template fit is used.

\[ \mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} = 0.71 \pm 0.17(\text{stat}) \pm 0.18(\text{syst}) \]

Systematic uncertainties dominated by $B_c \rightarrow J/\psi$ form factors and simulation size.

Result lies within $2\sigma$ of prediction from SM.
Use tree-level semileptonic decays to probe possible NP couplings.

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

\[ R(D^*) \text{ SM ratio: } 0.252 \pm 0.003 \]


Main Backgrounds:
- B\(\to\)Charmed Hadrons (DD*)
- B \(\to\) D**\(\nu\)

PRL 115 (2015) 111803
$R(D^*)$  

Signal extracted by 3D template fit ($q^2$, $m^2_{\text{miss}}$, $E_\mu$).  

Template obtained from simulated distributions.  

Main source of systematic uncertainties is sample size for template generation.  

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

Use the hadronic $\tau$ decay into 3 charged $\pi$.

Charged tracks allow vertexing for identifying $\tau$ decay point.

Use already measured BF of to obtain $R(D^*)$ from the relative measurement:

$$\kappa(D^{*-}) \equiv \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+\nu_\tau)}{\mathcal{B}(B^0 \to D^{*-}3\pi)}$$

$B^0 \to D^* \to K\pi$ and $B^0 \to D^* \to \mu\nu$, already measured.
R(D*) - Hadronic

Use the hadronic $\tau$ decay into 3 charged $\pi$.

Yields extracted from a fit to $q^2$, $\tau$ lifetime and kinematical BDT.

Using:

$$B(B^0 \to D^{*-}\mu^+\nu_\mu) = (4.88 \pm 0.10) \times 10^{-2}$$

$$B(B^0 \to D^{*-}3\pi) = (7.23 \pm 0.51) \times 10^{-3}$$

$$R(D^{*-}) = 0.286 \pm 0.019 \text{ (stat)} \pm 0.025 \text{ (syst)} \pm 0.021 \text{ (ext)}$$
R(D*) Status

LHCb results have been incorporated on world average compilation.

Currently R(D*) shows a tension of $3.4\sigma$ with respect to SM prediction.

http://www.slac.stanford.edu/xorg/hflav/semi/fpcp17/RDRDs.html
LFU in FCNC Processes
LFU probed with $b\to sll$

Small BR due to FCNC being forbidden in SM at tree level.

NP could produce a noticeable deviation from SM.

Different hadrons $H$ are sensitive to different Wilson Coefficient combinations.

\[ R_H \equiv \frac{\int_{4m_{\mu}^2}^{q_{\max}^2} dq^2 \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}}{\int_{4m_{\mu}^2}^{q_{\max}^2} dq^2 \frac{d\Gamma(B \to He^+e^-)}{dq^2}} \]

\[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\alpha_e}{4\pi} \sum_i C_i(\mu)\mathcal{O}_i(\mu) \]
$R(K)$

Measured using a double ratio

$1 < q^2 < 6 \text{ GeV}^2/c^4$

Events treated independently by trigger category.

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$L0 \ e$  
Electron caused trigger  

$L0 \ h$  

$L0 \ TIS$  
Kaon caused trigger  

Trigger caused by other particles

$R(K)$ in SM = 1.0029  
e.g. PRL 111, 162002 (2013)

$R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow \mu^+ \mu^-))} / \frac{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)}{\mathcal{B}(B^+ \rightarrow K^+ J/\psi (\rightarrow e^+ e^-))}$

Electron L0 Trigger J/psi  
Electron L0 Trigger Non resonant

$R_K = 0.745^{+0.090}_{-0.074} \text{(stat)} \pm 0.036 \text{(syst)}$

2.6 $\sigma$ from the SM!  
PRL 113, 151601 (2014)
$R(K^*)$

Also using a double ratio method.

4 body final state, $K^*$ reconstructed as $K^-\pi^+$

Use the measured B direction of flight to correct for electron Brem losses.

Corrected mass used as discriminant
$R(K^*)$

Also using a double ratio method.

Measured in two $q^2$ regions.

Control of efficiencies tested by measuring $J/\psi$ ratio.

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))} = 1.043 \pm 0.006 \pm 0.045$$

All 3 trigger categories combined in the fit.
$R(K^*)$

Also using a double ratio method.

Measured in two $q^2$ regions.

All 3 trigger categories combined in the fit.
\( R(K^*) \)

Also using a double ratio method.

Measured in two \( q^2 \) regions.

2.1-2.3\( \sigma \) from SM in the low \( q^2 \) bin

2.4-2.5\( \sigma \) from SM in the central \( q^2 \) bin

\[
R_{K^*0} = \begin{cases} 
0.66 \pm 0.11 \text{ (stat)} \pm 0.03 \text{ (syst)} & \text{for } 0.045 < q^2 < 1.1 \text{ GeV}^2/c^4 \\
0.69 \pm 0.11 \text{ (stat)} \pm 0.05 \text{ (syst)} & \text{for } 1.1 < q^2 < 6.0 \text{ GeV}^2/c^4 
\end{cases}
\]
**$B^+ \rightarrow K^+\mu^+\mu^-$ Phase Difference**

- Measurement of phase differences between long and short distance contributions.
- Probe whether or not tensions are coming from not well known SM processes.
- About 980,000 $B$ decays in the RunI sample.

B⁺ → K⁺μ⁺μ⁻ Phase Difference

Amplitude described in terms of Wilson Coefficients

Modelling of resonances using relativistic Breit-Wigner

Included in the q² fit: ω, ρ⁰, φ, J/ψ, ψ(2S), ψ(3770), ψ(4040), ψ(4415)

Fit has four solutions, ambiguity on the J/ψ and ψ(2S) phases.

c₇ constrained to SM value
B$^+ \rightarrow K^+\mu^+\mu^-$ Phase Difference

Amplitude described in terms of Wilson Coefficients

Assuming coefficients to be real.

Dominant uncertainty arises from B$\rightarrow$K Hadronic form factors.

$\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-) = (4.37 \pm 0.15 \text{ (stat)} \pm 0.23 \text{ (syst)}) \times 10^{-7}$
Conclusion

Very interesting set of anomalies observed in $b$-hadron decays.

LHCb has been able to probe very rare $b \rightarrow s \ell \ell$ and challenging $b \rightarrow c \ell \nu$ transitions.

LHCb will update all presented analysis with Run 2 data.

Other decays, such as $\Lambda_b \rightarrow p \ell \ell$, $B \rightarrow \phi \ell \ell$ are being investigated.
Backup
R(J/psi) SM predictions