



Bundesministerium für Bildung und Forschung

Tests of Lepton Flavour Universality and searches for Lepton Flavour Violation at LHCb

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Introduction: LFU

Lepton Flavour Universality (LFU): equal gauge boson couplings to leptons

• Well tested in weak couplings

 $Z \to \ell^+ \ell^- \quad \text{Phys. Rept. 427 (2006) 257}$ $\frac{\Gamma_{Z \to \mu^+ \mu^-}}{\Gamma_{Z \to e^+ e^-}} = 1.0009 \pm 0.0028$ $\frac{\Gamma_{Z \to \tau^+ \tau^-}}{\Gamma_{Z \to \mu^+ \mu^-}} = 1.0019 \pm 0.0032$

- Powerful probes for LFU tests and search for BSM effects:
 - $b
 ightarrow s\ell\ell
 ightarrow$ in this talk
 - $b \to c \ell \nu$



$b \rightarrow s \ell \ell$ transitions

• $b \rightarrow s\ell\ell$ decays proceed via FCNC transitions at loop order in the Standard Model



Effective field theory provides model independent description

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum C_i O_i$$

 C_i - Wilson coefficients, O_i - operators

- New particles modify decay rates and angular distributions
- Different *q*² regions probe different processes in the EFT framework



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The LHCb experiment



- Forward detector specialised in measuring properties of *b* and *c* hadrons
- Run 1 [2011-2012]: 7-8 TeV and 3 ${\rm fb}^{-1}$
- Run 2 [2015-2018]: 13 TeV and 6 ${
 m fb}^{-1}$

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LFU tests in $b \rightarrow s\ell\ell$ decays



- \mathcal{R}_{H_s} is unity in the SM
- Hadronic uncertainties cancel in the ratio
- Branching fractions and angular observables: affected by hadronic uncertainties Measurements of $B \rightarrow s\mu^{-}\mu^{+}$ processes at LHCb • A. Ward talk at Lepton Photon Angular distribution of $\Lambda_b \rightarrow pK^{-}\ell^{+}\ell^{-}$ decays comprising Λ resonances with spin < 5/2 • M. Kreps talk at Lepton Photon



Here focus on $\mathcal{R}_{\mathcal{K}}$ and $\mathcal{R}_{\mathcal{K}^*}$ determination with Run 1+2 LHCb data

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Simultaneous measurement of $\mathcal{R}_{\mathcal{K}}$ and $\mathcal{R}_{\mathcal{K}^*}$

Analysis strategy (example $\mathcal{R}_{\mathcal{K}}$): Double ratio of rare modes $B^+ \to \mathcal{K}^+ \ell^+ \ell^-$ and resonant modes $B^+ \to \mathcal{K}^+ J/\psi(\to \ell^+ \ell^-)$

$$\begin{aligned} \mathcal{R}_{K} &= \frac{\mathcal{B}(B^{+} \to K^{+}\mu^{+}\mu^{-})}{\mathcal{B}(B^{+} \to K^{+}e^{+}e^{-})} \times \frac{\mathcal{B}(B^{+} \to K^{+}J/\psi(e^{+}e^{-}))}{\mathcal{B}(B^{+} \to K^{+}J/\psi(\mu^{+}\mu^{-}))} \\ &= \left(\frac{N_{K^{+}\mu^{+}\mu^{-}}}{N_{K^{+}e^{+}e^{-}}}\right) \left(\frac{N_{K^{+}J/\psi(\to e^{+}e^{-})}}{N_{K^{+}J/\psi(\to \mu^{+}\mu^{-})}}\right) \times \left(\frac{\varepsilon_{K^{+}e^{+}e^{-}}}{\varepsilon_{K^{+}\mu^{+}\mu^{-}}}\right) \left(\frac{\varepsilon_{K^{+}J/\psi(\to e^{+}e^{-})}}{\varepsilon_{K^{+}J/\psi(\to e^{+}e^{-})}}\right) \end{aligned}$$

- Systematic effects from ε in e vs μ cancel largely in the double ratio
- Measurement in two q² regions:
 - low q^2 : [0.1, 1.0] GeV²
 - central q^2 : [1.1, 6.0] GeV²
- Challenges in different electron and muon reconstruction at LHCb
- Important cross checks: $r_{J/\psi} = 1$ and $r_{\psi(2S)}$
- First simultaneous analysis of *R_K* and *R_{K*}* in both *q²* bins with full LHCb dataset (accepted by PRL and PRD) → arXiv:2212.09152
 → arXiv:2212.09153

$\mathcal{R}_{\mathcal{K}}$ and $\mathcal{R}_{\mathcal{K}^*}$: electron reconstruction

Electron trigger:

- Lower e ε compared to muons due to tighter p_T threshold at L0 hardware trigger
- Trigger categories in analysis chosen to reduce impact of different hardware trigger in e/μ

Bremsstahlung:

- Energy loss due to bremsstrahlung
- Recovery procedure (50% efficient): look for photon cluster in ECAL compatible with *e* before the magnet
- Harder to control background and signal interplay



$\mathcal{R}_{\mathcal{K}}$ and $\mathcal{R}_{\mathcal{K}^*}$: background modelling

- Semileptonic backgrounds vetoed and particle swaps removed using specific PID criteria
- Partially reconstructed $(B \rightarrow K^{(*)}\ell\ell X)$: Dedicated MVA using isolation and m_{corr}
- **Combinatorial background**: MVA classifier using vertex and kinematic quantities
- Lepton and hadron misID data driven approach:
 - Invert *e* PID criteria to have background enriched samples
 - Weight backgrounds: $\omega = \frac{\epsilon_{passPID}}{\epsilon_{failPID}}$
 - Subtract signal contribution and obtain shapes of misID backgrounds



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\mathcal{R}_{K} and $\mathcal{R}_{K^{*}}$: $r_{J/\psi}$ and $r_{\psi(2S)}$

$$r_{J/\psi} = \frac{\mathcal{B}(B \to KJ/\psi(\to \mu^+ \mu^-))}{\mathcal{B}(B \to KJ/\psi(\to e^+ e^-))} = 1 \qquad \qquad r_{\psi(2S)} = \frac{\mathcal{B}(B \to K\psi(2S)(\to \mu^+ \mu^-))}{\mathcal{B}(B \to K\psi(2S)(\to e^+ e^-))} \times r_{J\psi}^{-1}$$



• Compatible with unity at 2σ

$\mathcal{R}_{\mathcal{K}}$ and $\mathcal{R}_{\mathcal{K}^*}$: invariant mass fits

Electron fits

- Tails from bremsstahlung from J/ψ in rare modes constrained
- Partially reconstructed K^{*0}e⁺e⁻ background constrained in K⁺e⁺e⁻

Muon fits

- Less background polluted than electrons
- All branching fractions consistent with previous measurements



\mathcal{R}_{K} and $\mathcal{R}_{K^{*}}$: results

- Dominant systematic uncertainty from misID backgrounds (2.0-2.5) %
- Most precise measurement of $\mathcal{R}_{\mathcal{K}}$ and $\mathcal{R}_{\mathcal{K}^*}$
- Compatible with standard model at 0.2 σ
- Statistically dominated



 R_K low- q^2 R_K central- q^2 R_{K^*} low- q^2 R_{K^*} central- q^2

$$\begin{split} \log -q^2 \begin{cases} R_K &= 0.994 \ \substack{+0.090 \\ -0.082} (\text{stat}) \ \substack{+0.029 \\ -0.027} (\text{syst}) \\ R_{K^*} &= 0.927 \ \substack{+0.093 \\ -0.087} (\text{stat}) \ \substack{+0.036 \\ -0.035} (\text{syst}) \end{cases} \\ \text{central-} q^2 \begin{cases} R_K &= 0.949 \ \substack{+0.042 \\ -0.021} (\text{stat}) \ \substack{+0.022 \\ -0.022} (\text{syst}) \\ R_{K^*} &= 1.027 \ \substack{+0.072 \\ -0.068} (\text{stat}) \ \substack{+0.027 \\ -0.026} (\text{syst}) \end{cases} \end{split}$$

$\mathcal{R}_{K^{*+}}$ and \mathcal{R}_{K_s} : results



- Measure $\mathcal{R}_{\mathcal{K}_{(s)}^{(*)}}$ with $B \to \mathcal{K}_s^0 \ell \ell$ and $B \to \mathcal{K}^{*+}(\to \mathcal{K}_s^0 \pi^+) \ell \ell$
- Use Run 1 + 2 data
- Large statisical uncertainty
- First observations of $B^+ \rightarrow K^{*+}(\rightarrow K_s^0 \pi^+)$ and $B^0 \rightarrow K_s^0 e^+ e^-$

$$\begin{split} \mathcal{R}_{\mathcal{K}^{*+}} = & 0.70^{+0.18}_{-0.13}(\mathrm{stat})^{+0.03}_{-0.04}(\mathrm{syst}) \\ \mathcal{R}_{\mathcal{K}_{S}} = & 0.70^{+0.18}_{-0.13}(\mathrm{stat})^{+0.03}_{-0.04}(\mathrm{syst}) \end{split}$$

Each measurement compatible with SM within \sim 1.5 σ

Introduction: LFV

Lepton Flavour is conserved in the Standard Model

- $\bullet~$ Violated for neutrinos \rightarrow neutrino oscillations
- Tensions with SM observed in LFU tests $(b \rightarrow s\ell\ell \text{ and } b \rightarrow c\ell\nu)$ motivate search for charged Lepton Flavour Violation (LFV) in $b \rightarrow se\mu$ and $b \rightarrow s\tau\mu$



Observation of LFV would be a clear sign of New Physics (NP)

 Limits on branching fractions constrain NP theories with Z', heavy neutrinos or leptoquarks • PRD D 92, 054013(2015)

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LFV with $B^0 o K^{*0} \mu^{\pm} e^{\mp}$ and $B_s o \phi \mu^{\pm} e^{\mp}$

- Search performed using Run 1 + 2
- Using ${\cal K}^{*0} \to {\cal K}^+ \pi^-$ and $\phi \to {\cal K}^+ {\cal K}^-$
- Normalisation relative to J/ψ modes: $B^0 \to K^{*0}J/\psi$ and $B^0_s \to \phi J/\psi$
- Vetoes for $B \rightarrow D^{(*)}\ell\nu$ decays and modeling for excited D mesons
- Upper limits at 90(95)% CL:

$$\begin{split} &\mathcal{B}(B^0\!\to\!K^{*0}e^+\mu^-)\!<\!6.8(7.9)\!\times\!10^{-9} \\ &\mathcal{B}(B^0\!\to\!K^{*0}e^-\mu^+)\!<\!5.7(6.9)\!\times\!10^{-9} \\ &\mathcal{B}(B^0\!\to\!K^{*0}e^\pm\mu^\mp)\!<\!10.1(11.7)\!\times\!10^{-9} \\ &\mathcal{B}(B^0\!\to\!\phi e^\pm\mu^\mp)\!<\!16.9(19.8)\!\times\!10^{-9} \end{split}$$

• Limits provided for NP scenarios of: $C_9^{\mu e} \neq 0$ and $C_9^{\mu e} = -C_{10}^{\mu e}$



LFV with $B^0 ightarrow K^{*0} au^{\pm} \mu^{\mp}$

- First search for this decay by any experiment
- Reconstructed with $au
 ightarrow 3\pi
 u_{ au}$
- Due to missing neutrinos *m_{corr}* used as a fitting variable

$$m_{corr}=\sqrt{p_{\perp}^2+m_{K^* au\mu}^2+p_{\perp}}$$

- $B^0
 ightarrow D^-(K^+\pi^-\pi^-)D^+_s(K^+K^-\pi^+)$ as normalisation
- No significant signal observed but limits at 90(95)% CL:

$$\begin{split} &\mathcal{B}(B^0 \!\!\rightarrow\!\! K^{*0} \tau^+ \mu^-) \!\!<\!\! 1.0(1.2) \!\times\! 10^{-5} \\ &\mathcal{B}(B^0 \!\!\rightarrow\!\! K^{*0} \tau^- \mu^+) \!\!<\!\! 8.2(9.8) \!\times\! 10^{-6} \end{split}$$



Summary

- Rare $b \to s \ell \ell$ transitions are excellent test bench for the SM and NP scenarios
- LHCb has performed the most precise LFU test (\mathcal{R}_K and \mathcal{R}_{K^*}) in $b \to s\ell\ell$ resulting with compatibility with SM
- LFV has been explored in $b
 ightarrow se(au) \mu$ with providing stringent limits
- Ongoing analyses aim for using the full LHCb dataset and as well exploiting angular structure of these decays:
 - LFU: \mathcal{R}_{ϕ} , \mathcal{R}_{Λ} , \mathcal{R}_{pK} , $\mathcal{R}_{K\pi\pi}$, \mathcal{R}_{K} and \mathcal{R}_{K^*} at high q^2
 - LFV: $B_s^0 \to \phi \mu^{\pm} \tau^{\mp}$, $\Lambda_b \to \Lambda e^{\pm} \mu^{\mp}$, $B_s^0 \to e^{\pm} \mu^{\mp}$
- Run 3 will provide more statistics with possibilities to enhance the precision in these measurements



Thank you!

BACKUP

$\mathcal{R}(K)$ and $\mathcal{R}(K^*)$: efficiency corrections



$\mathcal{R}(K)$ and $\mathcal{R}(K^*)$: misID backgrounds

• Invert PID requirements in electrons



 Categorise π and K electron misID based on DLL (difference in log likelihood of e to π) and ProbNN (MVA probability for PID)





$\mathcal{R}(K)$ and $\mathcal{R}(K^*)$: misID backgrounds

• Expected misID yields used in nominal fit to the rare modes



$\mathcal{R}(K)$ and $\mathcal{R}(K^*)$: invariant mass fits



$\mathcal{R}(K)$ and $\mathcal{R}(K^*)$: invariant mass fits



$\mathcal{R}(\mathcal{K})$ and $\mathcal{R}(\mathcal{K}^*)$: systematic uncertainty



LFV with $B^0 o K^{*0} \mu^\pm e^\mp$ and $B_s o \phi \mu^\pm e^\mp$

• Confidence limits at 90(95) %



LFV with $B^0 o K^{*0} \mu^{\pm} e^{\mp}$ and $B_s o \phi \mu^{\pm} e^{\mp}$

Results with NP models



→ JHEP 06 (2023) 073

LFV with $B^0
ightarrow K^{*0} au^{\pm} \mu^{\mp}$



LHCb Run 3 detector



