$B$-flavour anomalies in $b \rightarrow s \ell \ell$
and $b \rightarrow c \ell \nu$ transitions at LHCb

Olaf Steinkamp
on behalf of the LHCb collaboration
LHCb

Vertex locator

RICH detectors

Muon system

Tracking system

Calorimeters

2 < \eta < 5
Optimized for beauty and charm decays
Low-$p_T$ trigger thresholds
Excellent momentum and mass resolution
Unique particle-identification capabilities
Unique forward coverage

$2 < \eta < 5$
Results presented here based on Run-I data:

1 fb\(^{-1}\) at 7 TeV + 2 fb\(^{-1}\) at 8 TeV
\[ b \rightarrow c \ell^- \bar{\nu}_e \]
Test Lepton-Flavour Universality:

Weak coupling constant identical for all three lepton families

Possible violation e.g. due to extended Higgs sector or Leptoquarks:

Expected to couple predominantly to 3\textsuperscript{rd} family
Test Lepton-Flavour Universality:
by comparing decay rates, e.g.

\[ R(D^{(*)}) \equiv \frac{\text{BR} \left( B^0 \rightarrow D^{(*)+} \tau^- \bar{\nu}_\tau \right)}{\text{BR} \left( B^0 \rightarrow D^{(*)+} \mu^- \bar{\nu}_\mu \right)} \]

“Tree” decays:
→ Relatively large branching fractions (~ 1.2 %)
→ Well understood in Standard Model → precise predictions

Many systematics cancel to first order in ratio

But also experimentally challenging:
Multiple neutrinos from $W$ and $\tau$ decays
Determine $B$ flight direction from reconstructed vertices

Estimate $B$ momentum as

$$(p_B)_z \equiv \frac{m_B}{m_{\text{reco}}} \times (p_{\text{reco}})_z$$

Look at kinematic variables in the $B$ rest frame:

<table>
<thead>
<tr>
<th></th>
<th>$D^{*+} \tau^- \bar{\nu}_\tau$</th>
<th>$D^{*+} \mu^- \bar{\nu}_\mu$</th>
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</thead>
<tbody>
<tr>
<td>$E^*_\mu$</td>
<td>softer</td>
<td>harder</td>
</tr>
<tr>
<td>$m_{\text{miss}}^2$</td>
<td>$&gt; 0$</td>
<td>$\approx 0$</td>
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<tr>
<td>$q^2$</td>
<td>$&gt; m^2_\tau$</td>
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$R(D^*)$ with $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$

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

**Table:**

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**Graphs:**

- Candidates / (75 MeV)
  - Candidates / (0.3 GeV$^2$/c$^4$)

**References:**

[PRL 115(2015)111803]
\[ R(D^*) \text{ with } \tau^- \rightarrow \mu^- \nu_\mu \nu_\tau \]

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

2.1 \( \sigma \) above Standard Model prediction

Compatible with BaBar and Belle

Systematic uncertainty dominated by limited size of simulated event samples
Reconstruct $\tau$ decay vertex

Large background from

$B \rightarrow D^{*+} \pi^- \pi^+ \pi^- X$

→ Suppress using $\tau$ decay length

Long-lived background from

$B \rightarrow D^{*+} D^-_{(s)} X$ with $D^-_{(s)} \rightarrow \pi^- \pi^+ \pi^- X'$

→ Kinematics, Dalitz structure, partial reconstruction of $D$

→ Combine in BDT

$LHCb$ simulation

- Prompt ($D^*\pi\pi\pi X$)
- Double-charm ($D^*DX$)
- Signal ($D^*\tau\nu$)
Reconstruct $\tau$ decay vertex

Large background from
$$B \rightarrow D^{*+} \pi^- \pi^+ \pi^- X$$

→ Suppress using $\tau$ decay length

Long-lived background from
$$B \rightarrow D^{*+} D_{(s)}^- X \text{ with } D_{(s)}^- \rightarrow \pi^- \pi^+ \pi^- X'$$

→ Kinematics, Dalitz structure, partial reconstruction of $D$

→ Combine in BDT

$R(D^*)$ with $\tau^- \rightarrow \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$

[arxiv:1708.08856]
Reconstruct $\tau$ decay vertex

Large background from
$$B \rightarrow D^{*+} \pi^- \pi^+ \pi^- X$$

→ Suppress using $\tau$ decay length

Long-lived background from
$$B \rightarrow D^{*+} D^-_{(s)} X \text{ with } D^-_{(s)} \rightarrow \pi^- \pi^+ \pi^- X'$$

→ Kinematics, Dalitz structure, partial reconstruction of $D$

→ Combine in BDT
To reduce systematics, measure $BR$ relative to decay $B^0 \rightarrow D^{*+} \pi^- \pi^+ \pi^-$ with similar final state

$$R(D^*) = \frac{BR(B^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)}{BR(B^0 \rightarrow D^{*+} \pi^- \pi^+ \pi^-)} \times \frac{BR(B^0 \rightarrow D^{*+} \pi^- \pi^+ \pi^-)}{BR(B^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)}$$

systematic measurement

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

Systematic uncertainty again dominated by limited size of simulated event samples

(*) $BR(B^0 \rightarrow D^{*+} \pi^- \pi^+ \pi^-)$: LHCb, [PRD 87 (2013) 092001]  
$BR(B^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)$: HFLAV, [arxiv:1612.07233]
$R(D^*)$: Current Status

Combine with measurements of $R(D^*)$ and $R(D)$ from BaBar, Belle

All results above Standard Model predictions

$R(D^*)$ and $R(D)$ combined give $\sim 3 \sigma$ deviation, using latest Standard-Model predictions

[arXiv:1703.05330, 1707.09509, 1707.09977]
Test other $b$-systems, e.g.

\[
R(J/\psi) = \frac{\text{BR} \left( B_c^- \to J/\psi \tau^- \bar{\nu}_\tau \right)}{\text{BR} \left( B_c^- \to J/\psi \mu^- \bar{\nu}_\mu \right)}
\]

Standard Model predictions affected by form-factor uncertainties

\[ R_{SM}(J/\psi) \in [0.25, 0.28] \]

Small hadronisation fraction

\( \approx 0.2 \% \) for $B_c$ vs \( \approx 40 \% \) for $B^0$

→ Expect smaller statistics, larger systematic uncertainties
Approach similar to $R(D^*)$ measurement:

Reconstruct $B_c$ flight direction from production and decay vertices

Estimate $B_c$ momentum from

$$ (p_{Bc})_z \equiv \frac{m_{Bc}}{m_{reco}} \times (p_{reco})_z $$

Extract signal components from fit to decay time, $m^2_{\text{miss}}, Z(q^2, E^*)$
Approach similar to $R(D^*)$ measurement:

Reconstruct $B_c$ flight direction from production and decay vertices

Estimate $B_c$ momentum from

$$\left( \mathbf{p}_{B_c} \right)_z \equiv \frac{m_{B_c}}{m_{\text{reco}}} \times \left( \mathbf{p}_{\text{reco}} \right)_z$$

Extract signal components from fit to decay time, $m^2_{\text{miss}}$, $Z(q^2, E_\mu^*)$
$R(J/\psi)$ with $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$

Measured value about $2\sigma$ above Standard-Model predictions

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

Systematic uncertainty dominated by form-factor uncertainties and size of simulated event samples

Also: first evidence ($3\sigma$) for the decay

$$B_c^- \rightarrow J/\psi \, \tau^- \bar{\nu}_\tau$$

[arXiv:1711.05623]
$b \rightarrow s \ell^+ \ell^- : \quad R_{K^*} \text{ and } R_K$
Flavour-Changing Neutral Current decays

Suppressed in Standard Model, can only occur through loop processes

Excellent sensitivity to possible “New Physics” contributions

→ Branching fractions

→ Angular distributions
**$b \rightarrow s \ell^+ \ell^-$**

Perform measurements as a function of $q^2 = m^2(\ell^+\ell^-)$:

Different sensitivity to potential New Physics contributions

New Physics would affect Wilson coefficients $C_i$ in the effective Hamiltonian:

$$H_{\text{eff}} \equiv -\frac{4G_F}{\sqrt{2}} V_{tb} V^*_{ts} \sum_i \left\{ C_i O_i + C_i^\prime O_i^\prime \right\}$$

Relevant for $b \rightarrow s \ell^+ \ell^-$:

- $i = 7$: photon penguin
- $i = 9, 10$: electroweak penguins

Right-handed contributions strongly suppressed in Standard Model

$C_9^{(')}$ and $C_{10}^{(')}$ Long distance contributions from $c\bar{c}$ above open charm threshold

$J/\psi(1S)$
$\psi(2S)$
$b \rightarrow s \mu^+ \mu^-$ Branching Fractions

Measured values in the “interesting” $q^2$ range consistently below Standard-Model predictions

$B^+ \rightarrow K^+ \mu^+ \mu^-$  
[JHEP 06(2014)133]

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$  
[JHEP 04(2017)142]

$L_b \rightarrow \Lambda \mu^+ \mu^-$  
[PRD 93(2016)074501]

$B_s^0 \rightarrow \phi \mu^+ \mu^-$  
[JHEP 09(2015)179]
$b \rightarrow s \mu^+ \mu^-$ Branching Fractions

Measured values in the “interesting” $q^2$ range consistently below Standard-Model predictions

$B^+ \rightarrow K^+ \mu^+ \mu^-$
[JHEP 06(2014)133]

$B^0 \rightarrow K^* \mu^+ \mu^-$
[JHEP 04(2017)142]

$B^0_s \rightarrow \phi \mu^+ \mu^-$
[PRD 93(2016)074501]

But: significant theory uncertainties from hadronic form factors

$\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$
[JHEP 06(2015)115]

Detmold, Meinel
These form-factor uncertainties largely cancel in ratios:

\[ R_K \equiv \frac{\text{BR} (B^+ \to K^+ \mu^+ \mu^-)}{\text{BR} (B^+ \to K^+ e^+ e^-)} \]
These form-factor uncertainties largely cancel in ratios:

\[ R_{K^*} \equiv \frac{\text{BR} (B^0 \to K^* \mu^+ \mu^-)}{\text{BR} (B^0 \to K^* e^+ e^-)} \]
These form-factor uncertainties largely cancel in ratios:

\[ R_{K^*} \equiv \frac{\text{BR} (B^0 \rightarrow K^* \mu^+ \mu^-)}{\text{BR} (B^0 \rightarrow K^* e^+ e^-)} \]

→ Tests of Lepton Flavour Universality

Experimental challenge: Electron reconstruction

→ Algorithms for Bremstrahlung recovery, but never perfect
Lower trigger efficiencies $\rightarrow$ smaller statistics

Worse resolution, radiative tail of signal $\rightarrow$ have to consider partially reconstructed background at lower mass

Additional background from radiative tail of $J/\psi \rightarrow e^+e^-$
Measure $R_{K^*}$ in two bins of $q^2$

Measured values below Standard Model predictions:

2.1-2.3 $\sigma$ and 2.4-2.5 $\sigma$

$$R_{K^*} = \begin{cases} 
0.66^{+0.11}_{-0.07} \text{ (stat)} \pm 0.03 \text{ (syst)} & ; 0.045 < q^2 < 1.1 \text{ GeV}^2 c^4 \\
0.69^{+0.11}_{-0.07} \text{ (stat)} \pm 0.05 \text{ (syst)} & ; 1.1 < q^2 < 6.0 \text{ GeV}^2 c^4 
\end{cases}$$
BaBar and Belle also measured $R_{K^*}$, but larger uncertainties

![Graph showing $R_{K^*}$ vs $q^2$ with data points for LHCb, BaBar, and Belle]
Earlier measurement of $R_K$ for $1 < q^2 < 6 \text{ GeV}^2 c^4$
also below Standard Model, compatible at 2.6 $\sigma$

\[ R_K = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)} \; ; \; 1 < q^2 < 6 \text{ GeV}^2 c^4 \]
$b \rightarrow s \, \ell^+ \, \ell^- :$

angular observables
Angular Observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Reconstruct $K^{*0}$ in its decay to $K^+ \pi^-$

→ four final-state particles

→ three decay angles $(\theta_K, \theta_\ell, \phi)$

Angular distribution fully described by 8 independent coefficients

These are related to the underlying Wilson coefficients

To reduce dependence on hadronic form-factors, construct “optimized” observables such as

$$P'_5 \equiv \frac{S_5}{\sqrt{F_L (1-F_L)}}$$

[10.1007/JHEP1305(2013)137]
Measure the observables in bins of $q^2 = m^2(\ell^+\ell^-)$

→ Find deviations with local significance of $3.4\,\sigma$
for two $q^2$ bins in the observable $P_5'$
Belle, ATLAS, CMS also look at $P'_5$, but larger uncertainties

Belle measure $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ AND $B^0 \rightarrow K^{*0} e^+ e^-$

Possible Interpretations

Fits to $R_K$ and $R_{K^*}$ and angular observables give consistent picture:

→ Deviations can be explained with modifications either to $C_9$ or to $C_9$ and $C_{10}$

Charm-loop effects could contribute to $C_9$
but cannot explain Lepton-Flavour Universality observables
Possible Interpretations

Charm loop:

QCD contribution which at present cannot (yet) be computed reliably

Ciuchini et al. [arXiv:1512.07157]
Altmannshofer, Straub [arXiv:1503.06199]
Lyon, Zwicky [arXiv:1406.0566]

Possible New Physics contribution:

$\rightarrow Z'$ boson or Leptoquark, e.g.

Bordone et al. [PLB 779 (2018) 317]
Buttazzo et al. [JHEP 08 (2016) 035]
Barbieri et al. [EPJC 76 (2016) 67]
Greljo et al. [JHEP 07 (2015) 142]
Bauer et al. [PRL 116 (2016) 141802]
Crivellin et al. [PRL 114 (2015) 151801]
Altmannshofer et al. [PRD 89 (2014) 095033]
Diptomoy et al. [PRD 89 (2014) 071501]
Gould et al. [JHEP 01 (2014) 069]
Descote-Genon et al. [PRD 88 (2013) 074002]
Buras et al. [JHEP 12 (2013) 009]
Outlook
Summary

Intriguing tensions with Standard-Model predictions:

→ Branching Fractions of $b \rightarrow s \mu^+ \mu^-$ decays

→ Angular observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

→ Lepton Universality in $B^+ \rightarrow K^+ \ell^+ \ell^-$ and $B^0 \rightarrow K^{*0} \ell^+ \ell^-$

→ Lepton Universality in tree-level $B \rightarrow D(\ast)\ell\nu_\ell$ decays

Taken individually, none of these is very significant, taken together they might point to common pattern

Various explanations in terms of “New Physics”: $Z'$ boson, lepto-quarks, low-mass resonances, …

Or poorly understood hadronic effects, e.g. $c\bar{c}$ interference in $b \rightarrow s \ell\ell$?
Outlook

Run-2 updates of all measurements shown here
→ Expect ~ factor five in statistics

People are also working on other related analyses, e.g.

– $R(D), R(\Lambda_c^+)$

– Angular observables in $B^0 \rightarrow K^* e^+ e^-$

and more …
Outlook

LHCb Upgrade for LHC “long shutdown” (LS2) in 2019/2020:
→ Factor 5 in instantaneous luminosity
→ Improved trigger efficiency for hadrons

Expression of Interest for further LHCb Upgrades

Looking forward to friendly competition with Belle II here in Japan
Outlook

Close collaboration with theorists is crucial
We'll Be Happy!
Backup
Run II so far: 3.7 fb\(^{-1}\) at 13 TeV

\[ \sigma(pp \to b\bar{b}) : 300 \ \mu b \ @ \ 7 \ \text{TeV} \rightarrow 500 \ \mu b \ @ \ 13 \ \text{TeV} \]

Improvements in trigger and selection efficiencies
Test Lepton-Flavour Universality:

Weak coupling constant identical for all three lepton families

Tested in $W$ decays @ LEP to precision of a few percent

$$2 \times \frac{\text{BR} \left( W \to \tau^- \bar{\nu}_\tau \right)}{\text{BR} \left( W \to \mu^- \bar{\nu}_\mu \right) + \text{BR} \left( W \to e^- \bar{\nu}_e \right)} = 1.066 \pm 0.025 \left( \approx 2.6 \sigma \right)$$
$K^{(*)} e^+ e^- \text{ vs } K^{(*)} \mu^+ \mu^-$

Lower trigger efficiencies $\rightarrow$ smaller statistics

Worse resolution, radiative tail of signal $\rightarrow$ have to consider partially reconstructed background at lower mass

Additional background from radiative tail of $J/\psi \rightarrow e^+ e^-$

$\psi (2s)$
$J/\psi$

“central” “low”

[JHEP 08(2017)055]

April 17, 2018
DIS 2018 – B flavour anomalies @ LHCb (48)
O. Steinkamp
Measure $R_{K^*}$ in two bins of $q^2$

To reduce systematics, measure double ratio:

$$R_{K^*} \equiv \frac{\text{BR} \left( B^0 \rightarrow K^{*0} \mu^+ \mu^- \right) / \text{BR} \left( B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-) \right)}{\text{BR} \left( B^0 \rightarrow K^{*0} e^+ e^- \right) / \text{BR} \left( B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-) \right)} = 1$$

As a cross-check, determine also:

$$R_{\psi(2S)} \equiv \frac{\text{BR} \left( B^0 \rightarrow K^{*0} \psi(2S) (\rightarrow \mu^+ \mu^-) \right) / \text{BR} \left( B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-) \right)}{\text{BR} \left( B^0 \rightarrow K^{*0} \psi(2S) (\rightarrow e^+ e^-) \right) / \text{BR} \left( B^0 \rightarrow K^{*0} J/\psi (\rightarrow e^+ e^-) \right)}$$

Result compatible with expectation
Earlier measurement of $R_K$ for $1 < q^2 < 6$ GeV$^2$ c$^{-4}$

[PRL 113(2014)15601]
Angular Observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Angular acceptance in $(\theta_K, \theta_\ell, \phi)$ from simulation, cross checked on large samples of $B^0 \rightarrow K^{*0} J/\psi (\rightarrow \mu^+ \mu^-)$

- LHCB
  - $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
  - $B^0 \rightarrow J/\psi K^{*0}$

![Angular acceptance plots](image)

- Relative efficiency
  - $\cos \theta_K$
  - $\cos \theta_\ell$
  - $\phi$ [rad]