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1. Introduction
2. The LHCb detector
3. The anomalies
   - $b \rightarrow s \mu^+ \mu^-$ decay rates
   - $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ angular distributions: $P'_5$
   - Tests of Lepton Universality: $R_K$ and $R_{K^*}$
   - Interpretation
4. Conclusions and Outlook
1 Introduction

2 The LHCb detector

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4 Conclusions and Outlook
Rare decays in the SM

$\begin{array}{c}
\text{Possible contributions from NP} \\
\end{array}$

- Rare decays are so called Flavour Changing Neutral Currents
- In the SM: Only allowed via quantum fluctuations (loop suppressed)
- New heavy particles can significantly contribute to rare processes
- Change rates and angular distributions of rare decays
Rare decays as sensitive probes for New Physics

Rare decays in the SM

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Rare decays as sensitive probes for New Physics

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- New heavy particles can significantly contribute to rare processes
- Change rates and angular distributions of rare decays
NP contributions and relevant effective couplings

- Model independent description in effective field theory

\[ \mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i C_i O_i \]

- Flavour-violating coupling

\[ \Delta \mathcal{H}_{\text{NP}} = \frac{\Lambda^2_{\text{NP}}}{\kappa} O_i \]

- Wilson coefficient ("effective coupling")

- NP can contribute to different operators \( O_i \) depending on its type. Relevant effective couplings for rare decays:

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Operator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon penguin</td>
<td>( C_7^{(i)} ) ( \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu} )</td>
</tr>
<tr>
<td>EW penguin</td>
<td>( C_9^{(i)} ) ( (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu) )</td>
</tr>
<tr>
<td>Scalar penguin</td>
<td>( C_{10}^{(i)} ) ( (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \gamma_5 \mu) )</td>
</tr>
<tr>
<td></td>
<td>( C_S^{(i)} ) ( \frac{m_b}{m_B} (\bar{s}P_{R(L)} b)(\bar{\mu}\mu) )</td>
</tr>
<tr>
<td></td>
<td>( C_P^{(i)} ) ( \frac{m_b}{m_B} (\bar{s}P_{R(L)} b)(\bar{\mu}\gamma_5 \mu) )</td>
</tr>
</tbody>
</table>
The complementarity of NP searches with rare decays

**Exclusion limits for NP searches**

<table>
<thead>
<tr>
<th>scenario</th>
<th>$\kappa$</th>
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<tbody>
<tr>
<td>Tree generic</td>
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</tr>
<tr>
<td>Tree MFV</td>
<td>$V_{tb}V_{ts}$</td>
</tr>
<tr>
<td>Loop generic</td>
<td>$\frac{1}{16\pi^2}$</td>
</tr>
<tr>
<td>Loop MFV</td>
<td>$\frac{V_{tb}V_{ts}}{16\pi^2}$</td>
</tr>
</tbody>
</table>

- **Direct searches** limited by beam energy, $\Lambda_{NP} < \sqrt{s}$
- Reach with **rare decays** up to $\Lambda_{NP} \sim 100$ TeV, depending on coupling
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4. Conclusions and Outlook
- $b\bar{b}$ produced in forward/backward dir. $\rightarrow$ Forward spectrometer $2 < \eta < 5$

- Large $b\bar{b}$ ($c\bar{c}$) production cross-sections allows precision flavour measurements

- Run 1: $3 \text{ fb}^{-1}$, 2015-now: $5.2 \text{ fb}^{-1}$
The LHCb detector: Tracking

- Vertex detector
- Tracking system: TT
- Dipole magnet: 4 Tm
- Tracking system: IT and OT

Heavy flavour signature

- Excellent IP resolution $\sim 20 \mu m$
  $\rightarrow$ Identify secondary vertices from heavy flavour decays
- Momentum resolution $\frac{\Delta p}{p} \sim 0.5 - 1\%$ $\rightarrow$ Low combinatorial background
The LHCb detector: Particle identification

- Good $K\pi$ separation via RICH detectors: $\epsilon_{K\rightarrow K} \sim 95\%$, $\epsilon_{\pi\rightarrow K} \sim 5\%$
- Excellent muon identification: $\epsilon_{\mu\rightarrow \mu} \sim 97\%$, $\epsilon_{\pi\rightarrow \mu} \sim 1 - 3\%$

→ Reject backgrounds from misidentified $B$ decays (peaking backgrounds)
The LHCb detector: Flexible trigger system

- Low trigger thresholds ($p_T(\mu) > 1.76\text{ GeV}/c$ in 2012) and high efficiencies:
  $\epsilon_{B\rightarrow\mu\mu X} \sim 90\%$, $\epsilon_{\text{hadronic}} \sim 30\%$
- Full online detector calibration and alignment
Performance comparison: The decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

$N(B^0 \rightarrow K^{*0} \mu \mu) = 624 \pm 30$

$N(B^0 \rightarrow K^{*0} \ell \ell) = 50 \pm 8$

$N(B^0 \rightarrow K^{*0} \mu \mu) = 346 \pm 24$

$N(B^0 \rightarrow K^{*0} \mu \mu) = 275 \pm 35$
The anomalies | $b \rightarrow s\mu\mu$ decay rates

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Decay rates of $b \rightarrow s \mu^+ \mu^-$ processes sensitive to heavy BSM particles

Central quantity: $q^2 = m(\mu^+ \mu^-)^2$, different operators contribute depending on $q^2$

SM predictions affected by significant uncertainties from $q^2$-dependent hadronic form factors from non-perturbative calculations

- Low $q^2$: Light cone sum rules
- High $q^2$: Lattice QCD

$J/\psi(1S)$

$\psi(2S)$

$C_7^{(t)}$ interference

$C_9^{(t)}$ and $C_{10}^{(t)}$

Long distance contributions from $c\bar{c}$ above open charm threshold
Decay rates of $b \to s \mu^+ \mu^-$ processes sensitive to heavy BSM particles

Central quantity: $q^2 = m(\mu^+ \mu^-)^2$, different operators contribute depending on $q^2$

SM predictions affected by significant uncertainties from $q^2$-dependent hadronic form factors from non-perturbative calculations

The anomalies | $b \to s \mu \mu$ decay rates

$B^0 \to K^{*0}[\to K^+\pi^-]\mu^+\mu^-$ at LHCb

- BDT to suppress combinatorial background
  - Input variables: PID, kinematic and geometric quantities, isolation variables
- Veto $q^2$ range $[8, 11] \cup [12.5, 15]$ GeV$^2$/c$^4$ containing tree level decays $B^0 \to J/\psi K^{*0}$ and $B^0 \to \psi(2S)K^{*0}$ (important control modes)
- Signal clearly visible as vertical band after the full selection
The $B^0 \rightarrow K^{*0} [\rightarrow K^+\pi^-] \mu^+\mu^-$ branching fraction

\[ \frac{d\mathcal{B}(B^0 \rightarrow K^{*0}\mu^+\mu^-)}{dq^2} = \frac{1}{q^2_{\text{max}} - q^2_{\text{min}}} \times \frac{1 - F_{S}^{K^*}\mu\mu}{1 - F_{S}^{J/\psi}\mu^+\mu^-} \times \frac{N_{K^*}\mu\mu}{N_{J/\psi}} \times \frac{\epsilon_{K^*}\mu\mu}{\epsilon_{J/\psi}\mu^+\mu^-} \times \mathcal{B}(B^0 \rightarrow J/\psi K^{*0}) \times \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-) \]

- Measurement relative to normalisation mode $B^0 \rightarrow J/\psi K^{*0}$
- $\frac{\epsilon_{K^*}\mu\mu}{\epsilon_{J/\psi}\mu^+\mu^-}$ from (corrected) simulation, many effects cancel in ratio
- In agreement with but lower than SM prediction [arXiv:1503.05534] [PRD 89 (2014) 094501]
Similar to the rates of many other $b \to s\mu^+\mu^-$ decays!

- Data consistently below SM predictions (particularly at low $q^2$)
- Tensions at $1 - 3\sigma$ level, sizeable hadronic theory uncertainties
The anomalies

Angular distributions of $B^0 \rightarrow K^*0 \mu^+ \mu^-$

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Angular analysis of $B^0 \rightarrow K^{*0} \rightarrow K^+ \pi^- \mu^+ \mu^-$

- Decay fully described by three helicity angles $\Omega = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m_{\mu \mu}^2$
- \[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell 
- F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi 
+ S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi 
+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi 
+ S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right] \]

- $F_L, A_{FB}, S_i$ combinations of $K^{*0}$ spin amplitudes depending on Wilson coefficients $C_7^{(i)}, C_9^{(i)}, C_{10}^{(i)}$ and form factors

- Perform ratios of observables where form factors cancel at leading order

Example: $P'_5 = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$ [S. Descotes-Genon et al., JHEP, 05 (2013) 137]
The anomalies | Angular distributions of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Less form-factor dependent observable $P'_5$

- In $q^2$ bins $[4.0, 6.0]$ and $[6.0, 8.0]$ GeV$^2$/c$^4$ local deviations of 2.8σ and 3.0σ
- Global $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ analysis finds deviation corresponding to 3.4σ


- [PLB 781 (2018) 517] [arXiv:1805.04000]

C. Langenbruch (RWTH), QCD@LHC
The anomalies | Angular distributions of $B^0 \rightarrow K^{*0} \mu^+\mu^-$

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Lepton universality tests in rare decays

\[ R_h = \frac{\int \frac{d\Gamma(B \rightarrow h\mu^+\mu^-)}{dq^2} \, dq^2}{\int \frac{d\Gamma(B \rightarrow he^+e^-)}{dq^2} \, dq^2} \]
with \( h = K^+, K^{*0}, \phi, \ldots \)

- Extremely clean test of the SM: \( R_h^{SM} = 1 \pm \mathcal{O}(10^{-3}) \) (neglecting \( m_\ell \)), QED effects \( \mathcal{O}(10^{-2}) \) [EPJC 76 (2016) 440]
- Hadronic uncertainties (form factors etc.) cancel in the ratio
- Lepton universality can be violated in BSM models
- Orthogonal information from different \( h \) [PRD 96 (2017) 093006]
Most precise $R_h$ measurements with LHCb Run 1 data:

- $R_K$ [PRL 113 (2014) 151601]
- $R_{K^*}$ [JHEP 08 (2017) 055]

Use double ratio with resonant mode $B \rightarrow K^{(*)} J/\psi (\rightarrow \ell^+\ell^-)$

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

Double ratio cancels many systematic effects

Use normalisation mode to correct simulation and signal mass shape

Experimentally, the electron mode is more challenging at LHCb

1. Trigger ($p_T$ thresholds $\mu$: 1.8 GeV, $e$: 3.0 GeV in 2012)
2. Bremsstrahlung
Resolution degraded by energy loss from Bremsstrahlung
- Recovery of Bremsstrahlung not 100% efficient
- Recovery of Bremsstrahlung $\gamma$ in ECAL has limited resolution
\[
\frac{\sigma_E}{E} \sim 1\% \otimes \frac{10\%}{\sqrt{E\text{ (GeV)}}}
\]
- Contribution from partially reconstructed backgrounds
  e.g. $B^0 \to K^{*0} (\to K^+ \pi^-) \ell^+ \ell^-$ where $\pi^-$ is not reconstructed
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- Recovery of Bremsstrahlung not 100% efficient
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- Contribution from partially reconstructed backgrounds
  e.g. $B^0 \rightarrow K^{*0} (\rightarrow K^+ \pi^-) \ell^+ \ell^-$ where $\pi^-$ is not reconstructed
LHCb $R_K$ measurement (2014)

- LHCb determines $R_K$ in central $q^2$ region [1, 6] GeV$^2$:
  $$R_K = 0.745^{+0.090}_{-0.074} \text{(stat.)} \pm 0.036 \text{(syst.)},$$
- Compatible with SM at $2.6\sigma$
\( R_{K^*} : \) data after preselection

\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \]

\[ B^0 \rightarrow K^{*0} e^+ e^- \]

- Similar to \( R_K \):
  - Bremsstrahlung (recovery)
  - Partially reconstructed backgrounds, e.g. \( B^+ \rightarrow K^+ \pi^+ \pi^- \ell^+ \ell^- \)

- Determine \( R_{K^*} \) in two regions of \( q^2 \):
  - Low \( q^2 \): \( q^2 \in [0.045, 1.1] \) GeV\(^2\)
  - Central \( q^2 \): \( q^2 \in [1.1, 6.0] \) GeV\(^2\)
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

**Low $q^2$: 285 ± 18**  
**Central $q^2$: 353 ± 21**  
**$J/\psi$: 274 k**

$B^0 \rightarrow K^{*0} e^+ e^-$

**Low $q^2$: 89 ± 11**  
**Central $q^2$: 111 ± 14**  
**$J/\psi$: 58 k**
The anomalies

Tests of lepton universality

$R_{K^*}$ Results

Compatibility with SM prediction(s):

- 2.1-2.3 standard deviations at low $q^2$
- 2.4-2.5 standard deviations at central $q^2$

Compatible with Babar and Belle with smaller uncertainties
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   - Tests of Lepton Universality: $R_K$ and $R_{K^*}$
   - Interpretation

4 Conclusions and Outlook
Global fits without $R_{K,K^*}$

- Global fit of the $b \to s \mu^+ \mu^-$ measurements incl. $\mathcal{B}$ and angular obs.
- Tensions can be reduced by shift in $C_9$, significances $\sim 4-5 \sigma$
- Consistency between angular observables and branching fractions
- Many other global fits [arxiv:1704.05340] [JHEP 06 (2016) 092] [NPB 909 (2016) 737] …

<table>
<thead>
<tr>
<th>Coeff.</th>
<th>best fit</th>
<th>$1\sigma$</th>
<th>pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_9^{NP}$</td>
<td>$-1.21$</td>
<td>$[-1.41, -1.00]$</td>
<td>$5.2\sigma$</td>
</tr>
<tr>
<td>$C_9'$</td>
<td>$+0.19$</td>
<td>$[-0.01, +0.40]$</td>
<td>$0.9\sigma$</td>
</tr>
<tr>
<td>$C_{10}^{NP}$</td>
<td>$+0.79$</td>
<td>$[+0.55, +1.05]$</td>
<td>$3.4\sigma$</td>
</tr>
<tr>
<td>$C_{10}'$</td>
<td>$-0.10$</td>
<td>$[-0.26, +0.07]$</td>
<td>$0.6\sigma$</td>
</tr>
<tr>
<td>$C_9^{NP} = C_9^{NP}$</td>
<td>$-0.30$</td>
<td>$[-0.50, -0.08]$</td>
<td>$1.3\sigma$</td>
</tr>
<tr>
<td>$C_9^{NP} = -C_{10}^{NP}$</td>
<td>$-0.67$</td>
<td>$[-0.83, -0.52]$</td>
<td>$4.8\sigma$</td>
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<td>$C_9' = C_9'$</td>
<td>$+0.06$</td>
<td>$[-0.18, +0.30]$</td>
<td>$0.3\sigma$</td>
</tr>
<tr>
<td>$C_9' = -C_{10}'$</td>
<td>$+0.08$</td>
<td>$[-0.02, +0.18]$</td>
<td>$0.8\sigma$</td>
</tr>
<tr>
<td>$C_9^{NP}$, $C_{10}^{NP}$</td>
<td>$(-1.15, +0.26)$</td>
<td>—</td>
<td>$5.0\sigma$</td>
</tr>
<tr>
<td>$C_9^{NP}$, $C_9'$</td>
<td>$(-1.25, +0.59)$</td>
<td>—</td>
<td>$5.3\sigma$</td>
</tr>
<tr>
<td>$C_9^{NP}$, $C_9'$</td>
<td>$(-1.34, -0.39)$</td>
<td>—</td>
<td>$5.4\sigma$</td>
</tr>
<tr>
<td>$C_9'$, $C_{10}^{NP}$</td>
<td>$(+0.25, +0.83)$</td>
<td>—</td>
<td>$3.2\sigma$</td>
</tr>
<tr>
<td>$C_9'$, $C_{10}'$</td>
<td>$(+0.23, +0.04)$</td>
<td>—</td>
<td>$0.5\sigma$</td>
</tr>
<tr>
<td>$C_9^{NP}$, $C_{10}'$</td>
<td>$(+0.79, -0.05)$</td>
<td>—</td>
<td>$3.0\sigma$</td>
</tr>
</tbody>
</table>
Possible NP

Assuming NP, shift in $\Delta C_9$ can be related to scale $\Lambda_{NP}$:

$$\Lambda_{NP} = \sqrt{\frac{\kappa}{\Delta C_9}} \frac{\sqrt{2}}{4G_F} \frac{4\pi}{\alpha V_{tb}V_{ts}^*}$$

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\kappa$</th>
<th>$\Lambda_{NP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree generic</td>
<td>1</td>
<td>$\sim 36$ TeV</td>
</tr>
<tr>
<td>Tree MFV</td>
<td>$V_{tb}V_{ts}$</td>
<td>$\sim 7$ TeV</td>
</tr>
<tr>
<td>Loop generic</td>
<td>$\frac{1}{16\pi^2}$</td>
<td>$\sim 2.8$ TeV</td>
</tr>
<tr>
<td>Loop MFV</td>
<td>$\frac{V_{tb}V_{ts}}{16\pi^2}$</td>
<td>$\sim 0.6$ TeV</td>
</tr>
</tbody>
</table>

Possible explanations for shift in $C_9$

3. $q^2$ dependence: $c\bar{c}$ loops rise towards $J/\psi$, NP $q^2$-independent
4. $c\bar{c}$ loops lepton flavour universal

For details see talk by D. v. Dyk
New Physics or QCD(@LHC)?

Possible explanations for shift in $C_9$

1. **NP e.g. $Z'$**
   - [Gauld et al.]
   - [Buras et al.]
   - [Altmannshofer et al.]
   - [Crivellin et al.]

2. **Leptoquarks**
   - [Hiller et al.]
   - [Biswas et al.]
   - [Buras et al.]
   - [Gripaios et al.]

3. **hadronic charm loop contributions**
   → For details see talk by D. v. Dyk

- $q^2$ dependence: $c\bar{c}$ loops rise towards $J/\psi$, NP $q^2$-independent
- $c\bar{c}$ loops lepton flavour universal
Impact of $R_{K,K^*}$ in global fits

- Theoretically clean LFU measurements alone give $\sim 4\sigma$
- Constraints from $B$ and angular obs. consistent with $R_{K,K^*}$
- Further increase tensions with SM [PRD 96 (2017) 055008]
- Enlarging hadronic uncertainties by factor 5 shows $b \rightarrow s\mu\mu$ $B$ and angular observables still give additional constraints
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4. Conclusions and Outlook
Conclusions

- Rare $B$ decays are an excellent laboratory to search for NP. LHCb provides an ideal environment to study these decays.

- Most measurements are in good agreement with SM predictions, setting strong constraints on NP.

- However, several anomalies have emerged:
  - Low branching ratio of $b \to s \mu\mu$ decays: significances $\sim 1-3\sigma$.
  - Angular observables in $B^0 \to K^{*0}\mu^+\mu^-$: significance $\sim 3\sigma$.
  - Lepton universality tests $R_{K, K^*}$: combined significance $\sim 4\sigma$.

- Consistent NP explanations of all anomalies exist.

- Subset of anomalies potentially affected by QCD $c\bar{c}$-loops.
Outlook

- Most measurements only use Run 1 data and are statistically limited
- Many Run 2 measurements in preparation: Stay tuned!
- Full Run 2 data expected to more than quadruple statistics
- Future LHCb Upgrades will allow high statistics measurements
- Belle 2 joins with full detector soon, will allow indep. clarification of anomalies
- CMS/ATLAS also investing significant resources

---

### Naive scaling with $\sqrt{s}$ and luminosity

<table>
<thead>
<tr>
<th>Yield</th>
<th>Run 1 result</th>
<th>9 fb$^{-1}$</th>
<th>50 fb$^{-1}$</th>
<th>300 fb$^{-1}$</th>
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</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K^{*0}\mu^+\mu^-$</td>
<td>2398±57</td>
<td>10530</td>
<td>70400</td>
<td>435000</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+\mu^+\mu^-$</td>
<td>4767±81</td>
<td>20840</td>
<td>139300</td>
<td>862000</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \phi\mu^+\mu^-$</td>
<td>432±24</td>
<td>1900</td>
<td>12700</td>
<td>78000</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+e^+e^-$</td>
<td>254 ± 29</td>
<td>1120</td>
<td>7500</td>
<td>46000</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^*0e^+e^-$</td>
<td>111 ± 14</td>
<td>490</td>
<td>3300</td>
<td>20000</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \phi e^+e^-$</td>
<td>—</td>
<td>80</td>
<td>530</td>
<td>3300</td>
</tr>
</tbody>
</table>
LHCb prospects for rare $b \rightarrow s \ell \ell$ decays

Measurements of rare $b \rightarrow s \ell \ell$ decays generally statistically dominated

Updates with Run 2 data ongoing

4.4 fb$^{-1}$ of Run 2 data on tape $\rightarrow$ already roughly triples signal yields

Large data samples allow new analysis techniques

New decay modes and analyses become accessible

Naive scaling with $\sqrt{s}$ and luminosity

<table>
<thead>
<tr>
<th>Observable</th>
<th>Run 1 result</th>
<th>8 fb$^{-1}$</th>
<th>50 fb$^{-1}$</th>
<th>300 fb$^{-1}$</th>
</tr>
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<tbody>
<tr>
<td>$B^0 \rightarrow K^{*0} \mu^+ \mu^-$</td>
<td>2398 ± 57</td>
<td>9180</td>
<td>70500</td>
<td>435000</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow \phi \mu^+ \mu^-$</td>
<td>432 ± 24</td>
<td>1650</td>
<td>12700</td>
<td>78000</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+ \mu^+ \mu^-$</td>
<td>4746 ± 81</td>
<td>18160</td>
<td>139500</td>
<td>862000</td>
</tr>
<tr>
<td>$B^+ \rightarrow \pi^+ \mu^+ \mu^-$</td>
<td>93 ± 12</td>
<td>360</td>
<td>2700</td>
<td>17000</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$</td>
<td>373 ± 25</td>
<td>1430</td>
<td>11000</td>
<td>68000</td>
</tr>
<tr>
<td>$1 B^+ \rightarrow K^+ e^+ e^-$</td>
<td>254 ± 29</td>
<td>970</td>
<td>7500</td>
<td>46000</td>
</tr>
<tr>
<td>$1 B^0 \rightarrow K^{*0} e^+ e^-$</td>
<td>111 ± 14</td>
<td>430</td>
<td>3300</td>
<td>20000</td>
</tr>
</tbody>
</table>

$1 < q^2 < 6.0 \text{ GeV}^2$
New approaches to $b \rightarrow s \ell \ell$ decays

- $q^2$-unbinned approaches allow to better exploit the data [JHEP 11 (2017) 176]
- Major challenge to disentangle NP from charm-loop contribution in $C_9$
- Different parameterisations of the charm-loop contributions on the market
  - Parameterisation using Breit-Wigners [EPJC 78 (2018) 453]
  - Parameterisation from analyticity [arXiv:1805.06378] [arXiv:1805.06401]
Currently analyzing Run 2 data to update $R_K$ and $R_{K^*}$

Additional ratios are also under study $R_\phi$, $R_{pK}$, $R_{K\pi\pi}$

LFU in angular distribution:
$$D_{P'_5} = P'_5(B^0 \rightarrow K^{*0} \mu^+ \mu^-) - P'_5(B^0 \rightarrow K^{*0} e^+ e^-)$$

Extremely clean SM predictions for these angular observables
Lepton non-universality generally implies Lepton Flavour violation

[Glashow et al., PRL 114 (2015) 091801]

Motivates searches for $B^+ \rightarrow K^+ \mu^\pm e^\mp$, $B^0 \rightarrow K^{*0} \mu^\pm e^\mp$, ...

Branching fractions just below current upper limits possible

Observation of LFV modes would be a clear sign of NP

LHCb will probe below current limits for $B \rightarrow X e \mu$

Decays with $\tau$ final states more challenging, but improvements possible
Current status: Well on the way to 8 fb\(^{-1}\) in Run 1+2

Upgrade I a+b: 50 fb\(^{-1}\) after Run 3+4 at \(\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}\)

Upgrade II: 300 fb\(^{-1}\) after Run 5 at \(\mathcal{L} = 2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\)

How does this impact the NP reach of Rare Decays?
\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \] Results: \( F_L, A_{FB} \) and \( S_5 \)

- Generally good agreement with SM predictions
- Mild tension in \( A_{FB} \)
- Some tension in \( S_5 \)

![Graphs showing \( F_L \), \( A_{FB} \), and \( S_5 \) vs. \( q^2 \) for LHCb data compared to SM predictions from ABSZ.](image)
- Background subtracted, normalized to same area
- Good agreement between electrons/muons and data/simulation
### Likelihood Fit

**Low-$q^2$**

- $R_{K^{*0}}$: $0.66 \pm 0.11 \pm 0.07 \pm 0.03$
- $95.4\%$ CL: $[0.52, 0.89]$
- $99.7\%$ CL: $[0.45, 1.04]$

**Central-$q^2$**

- $R_{K^{*0}}$: $0.69 \pm 0.11 \pm 0.07 \pm 0.05$
- $95.4\%$ CL: $[0.53, 0.94]$
- $99.7\%$ CL: $[0.46, 1.10]$

- Good agreement between trigger categories
A simple example: The very rare decay $B^0_{(s)} \rightarrow \mu^+ \mu^-$

- Loop and additionally helicity suppressed
- Purely leptonic final state: Theoretically and experimentally very clean
- Very sensitive to NP: Possible scalar and pseudoscalar enhanced wrt. SM axialvector

$B \propto |V_{tb}V_{tq}|^2 \left[ (1 - \frac{4m^2_{\mu}}{M^2_B}) |C_S - C'_S|^2 + |(C_P - C'_P) + \frac{2m^2_{\mu}}{M^2_B} (C_{10} - C'_{10})|^2 \right]$

SM prediction [C. Bobeth et al., PRL 112, 101801 (2014)]

$\mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (3.65 \pm 0.23) \times 10^{-9}$
$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$
Determination of the $B_{(s)}^0 \rightarrow \mu^+ \mu^-$ branching fraction

- Analysis of LHCb data $3 \text{ fb}^{-1} (2011+2012)$ and $1.4 \text{ fb}^{-1} (2015+2016)$ [PRL 118 (2017) 191801]
- Observation of $B_{s}^0 \rightarrow \mu^+ \mu^-$ with $7.8 \sigma$ significance
  $\mathcal{B}(B_{s}^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$
- No excess of $B^0 \rightarrow \mu^+ \mu^-$ observed ($1.6 \sigma$)
  $\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.5^{+1.2}_{-1.0}^{+0.2}_{-0.1}) \times 10^{-10}$
- Ratio $\mathcal{R} = \frac{\mathcal{B}(B_{s}^0 \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B_{s}^0 \rightarrow \mu^+ \mu^-)} \overset{\text{MFV}}{=} \left| \frac{V_{td}}{V_{ts}} \right|^2$ test of MFV: Good agreement with SM

C. Langenbruch (RWTH), QCD@LHC

Flavour Anomalies
The $B^0_S \rightarrow \mu^+\mu^-$ effective lifetime

- Effective Lifetime complementary probe for New Physics
- $\tau_{\mu\mu} \approx \tau_{B_S} (1 + y_S A_{\Delta\Gamma})$ with $y_S = \tau_{B_S} \frac{\Delta\Gamma^S}{2} = 0.062 \pm 0.006$
  In SM: $A_{\Delta\Gamma} = +1$, NP models $A_{\Delta\Gamma} \in [-1, +1]$
- $\tau (B^0_S \rightarrow \tau^+\tau^-) = 2.04 \pm 0.44 \pm 0.05$ ps,
  Compatible with $A_{\Delta\Gamma} = +1 (-1)$ at $1.0 \sigma (1.4 \sigma)$
- $B^0_{(s)} \rightarrow \mu^+\mu^-$ in good agreement with SM!
In the MSSM: $\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) \propto \tan^6 \beta / m_A^4$

Complementarity with direct searches

In the future, $B_s^0 \rightarrow \mu^+ \mu^-$ effective lifetime will allow to exclude second solution (with opposite sign of amplitude)

→ Strong constraints, Looking forward to more data!
The anomalies | Tests of lepton universality

Test of lepton universality in $B \rightarrow D^{(*)} \ell \nu$ decays

- Hints of non-lepton universality also in $R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \mu^- \bar{\nu}_\mu)}$
- Deviation of $R_{D^{(*)}}$ from SM prediction at 4$\sigma$ level
Alternative fit

The anomalies | Tests of lepton universality

C. Langenbruch (RWTH), QCD@LHC

Flavour Anomalies
$B_s^0 \rightarrow \mu^+ \mu^-$ crucial as clean probe of $C_{10}$
Bremsstrahlung in data and simulation

Fraction of candidates [%]

0 clusters
1 cluster
≥2 clusters

LHCb
$B^0 \rightarrow K^{*0} J/\psi$

Data
Simulation

[JHEP 08 (2017) 055]
Trigger, reconstruction and selection distorts decay angles and $q^2$ distribution

Parametrize 4D efficiency using Legendre polynomials $P_k$

$$\varepsilon(\cos \theta_\ell, \cos \theta_K, \phi, q^2) = \sum_{klmn} c_{klmn} P_k(\cos \theta_\ell) P_l(\cos \theta_K) P_m(\phi) P_n(q^2)$$

$c_{klmn}$ from moments analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ phase-space MC

Crosscheck acceptance using $B^0 \rightarrow J/\psi K^{*0}$ control decay
Control decay $B^0 \rightarrow J/\psi K^{*0}$

- **black line**: full fit, **blue**: signal component, **red**: bkg. part
- Angular observables successfully reproduced [PRD 88, 052002 (2013)]
S-wave pollution

- **S-wave**: $K^+\pi^-$ not from $K^*^0(892)$ but in spin 0 configuration
- Introduces two add. decay amplitudes resulting in six add. observables

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} \bigg|_{S+P} = (1 - F_S) \frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^3(\Gamma + \bar{\Gamma})}{d\vec{\Omega}} \bigg|_P \\
+ \frac{3}{16\pi} F_S \sin^2 \theta_\ell + \text{S-P interference}
\]

- $F_S$ scales P-wave observables, needs to be determined precisely

- Perform simultaneous $m_{K^+\pi^-}$ fit to constrain $F_S$
- P-wave described by rel. Breit-Wigner
- S-wave described by LASS model crosschecked using Isobar param.
First full angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- First full angular analysis [JHEP 02 (2016) 104] in bins of $q^2$
- Efficiency corrected distributions show good agreement with overlaid projections of the probability density function
The anomalies | Tests of lepton universality

\( B^0 \rightarrow K^{*0} \mu^+ \mu^- \) Results: \( F_L, A_{FB} \) and \( S_5 \)

- Generally good agreement with SM predictions
- Mild tension in \( A_{FB} \)
- Some tension in \( S_5 \)

\[ q^2 \, [\text{GeV}^2/c^4] \]
The anomalies | Tests of lepton universality

Less form-factor dependent observable $P'_5$

- In $q^2$ bins [4.0, 6.0] and [6.0, 8.0] GeV$^2$/c$^4$ local deviations of 2.8$\sigma$ and 3.0$\sigma$
- Global $B^0 \rightarrow K^{*0}\mu^+\mu^-$ analysis finds deviation corresponding to 3.4$\sigma$
Less form-factor dependent observable $P'_5$

- In $q^2$ bins $[4.0, 6.0]$ and $[6.0, 8.0]$ GeV$^2/c^4$ local deviations of $2.8\sigma$ and $3.0\sigma$
- Global $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ analysis finds deviation corresponding to $3.4\sigma$
### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$F_L$</th>
<th>$S_{3-9}$</th>
<th>$A_{3-9}$</th>
<th>$P_{1-8}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance stat. uncertainty</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>Acceptance polynomial order</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.02$</td>
<td>$&lt; 0.02$</td>
<td>$&lt; 0.04$</td>
</tr>
<tr>
<td>Data-simulation differences</td>
<td>0.01–0.02</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>Acceptance variation with $q^2$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>$m(K^+\pi^-)$ model</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.03$</td>
</tr>
<tr>
<td>Background model</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td>Peaking backgrounds</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>$m(K^+\pi^-\mu^+\mu^-)$ model</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td>Det. and prod. asymmetries</td>
<td>–</td>
<td>–</td>
<td>$&lt; 0.01$</td>
<td>$&lt; 0.02$</td>
</tr>
</tbody>
</table>

- Systematic uncertainties determined using high statistics toys
- Measurement is statistically dominated (and will still be in Run 2)
The anomalies | Tests of lepton universality

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ Results: $F_L$, $S_3$, $S_4$, $S_5$

$F_L$

$LHCb$

[SM from ABSZ]

$S_3$

$LHCb$

[SM from ABSZ]

$S_4$

$LHCb$

[SM from ABSZ]

$S_5$

$LHCb$

[SM from ABSZ]

C. Langenbruch (RWTH), QCD@LHC
The anomalies | Tests of lepton universality

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ results: $A_{FB}, S_7, S_8, S_9$

$A_{FB}$

$S_7$

$S_8$

$S_9$
The anomalies | Tests of lepton universality

$B^0 \rightarrow K^{*0} \mu^+ \mu^- \ CP$ asymmetries: $A_3, A_4, A_5, A_{6s}$

\begin{align*}
A_3 & \\
A_4 & \\
A_5 & \\
A_{6s} & 
\end{align*}

$q^2 [\text{GeV}^2/c^4]$
The anomalies
Tests of lepton universality

\( B^0 \to K^{*0} \mu^+ \mu^- \) \( CP \) asymmetries: \( A_7, A_8, A_9 \)

\[ A_7, A_8, A_9 \]

\[ q^2 \text{[GeV}^2/c^4] \]

LHCb
The anomalies

Tests of lepton universality

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: $P_1$, $P_2$, $P_3$, $P_4'$

$P_1$

$LHCb$

- SM from DHMV

$q^2 [\text{GeV}^2/c^4]$

$P_2$

$LHCb$

- SM from DHMV

$q^2 [\text{GeV}^2/c^4]$

$P_3$

$LHCb$

- SM from DHMV

$q^2 [\text{GeV}^2/c^4]$

$P_4'$

$LHCb$

- SM from DHMV

$q^2 [\text{GeV}^2/c^4]$
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$: $P'_5$, $P'_6$, $P'_8$

LHCb

SM from DHMV

$q^2 [\text{GeV}^2/c^4]$

JHEP 02 (2016) 104
Perform $\chi^2$ fit of measured $S_i$ observables using [EOS] software
Varying Re($C_9$) and incl. nuisances according [F. Beaujean et al., EPJC 74 (2014) 2897]
$\Delta\text{Re}(C_9) = -1.04 \pm 0.25$ with global significance of 3.4 $\sigma$
The anomalies

Tests of lepton universality

$I_i(q^2)$ depend on $K^0\pi^0$ spin amplitudes $A_{0,R}^{L,R}, A_{\parallel,R}^{L,R}$

\[ I_1^s = \frac{(2 + \beta_\mu^2)}{4} [A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R)] + \frac{4m_\mu^2}{q^2} \Re(A_\perp^L A_\perp^R* + A_\parallel^L A_\parallel^R*) \]

\[ I_1^c = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\mu^2}{q^2} [|A_i|^2 + 2\Re(A_0^L A_0^R*)] \]

\[ I_2^s = \frac{\beta_\mu^2}{4} \left\{ |A_\perp^L|^2 + |A_\parallel^L|^2 + (L \to R) \right\} \]

\[ I_2^c = -\beta_\mu^2 \left\{ |A_0^L|^2 + (L \to R) \right\} \]

\[ I_3 = \frac{\beta_\mu^2}{2} \left\{ |A_\perp^L|^2 - |A_\parallel^L|^2 + (L \to R) \right\} \]

\[ I_4 = \frac{\beta_\mu^2}{\sqrt{2}} \left\{ \Re(A_0^L A_\parallel^L*) + (L \to R) \right\} \]

\[ I_5 = \sqrt{2}\beta_\mu \left\{ \Re(A_0^L A_\perp^L*) - (L \to R) \right\} \]

\[ I_6 = 2\beta_\mu \left\{ \Re(A_\parallel^L A_\perp^L*) - (L \to R) \right\} \]

\[ I_7 = \sqrt{2}\beta_\mu \left\{ \Im(A_0^L A_\perp^L*) - (L \to R) \right\} \]

\[ I_8 = \frac{\beta_\mu^2}{\sqrt{2}} \left\{ \Im(A_0^L A_\parallel^L*) + (L \to R) \right\} \]

\[ I_9 = \beta_\mu^2 \left\{ \Im(A_\parallel^L A_\perp^L*) + (L \to R) \right\} \]
The anomalies | Tests of lepton universality

$K^*0$ spin amplitudes $A^{L,R}_0$, $A^{L,R}_\parallel$, $A^{L,R}_\perp$

$A^{L(R)}_\perp = N \sqrt{2}\lambda \left\{ \left[ (C^\text{eff}_9 + C'^\text{eff}_9) \mp (C^\text{eff}_{10} + C'^\text{eff}_{10}) \right] \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} (C^\text{eff}_7 + C'^\text{eff}_7) T_1(q^2) \right\}$

$A^{L(R)}_\parallel = -N \sqrt{2}(m_B^2 - m_{K^*}^2) \left\{ \left[ (C^\text{eff}_9 - C'^\text{eff}_9) \mp (C^\text{eff}_{10} - C'^\text{eff}_{10}) \right] \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} (C^\text{eff}_7 - C'^\text{eff}_7) T_2(q^2) \right\}$

$A^{L(R)}_0 = -\frac{N}{2m_{K^*}\sqrt{q^2}} \left\{ \left[ (C^\text{eff}_9 - C'^\text{eff}_9) \mp (C^\text{eff}_{10} - C'^\text{eff}_{10}) \right] \left[ (m_B^2 - m_{K^*}^2 - q^2)(m_B + m_{K^*}) A_1(q^2) - \lambda \frac{A_2(q^2)}{m_B + m_{K^*}} \right] 

+ 2m_b(C^\text{eff}_7 - C'^\text{eff}_7)[(m_{K^*}^2 - q^2) T_2(q^2) - \frac{\lambda}{m_B^2 - m_{K^*}^2} T_3(q^2)] \right\}$

- Wilson coefficients $C^{(i)\text{eff}}_{7,9,10}$

- Seven form factors (FF) $V(q^2)$, $A_{0,1,2}(q^2)$, $T_{1,2,3}(q^2)$ encode hadronic effects and require non-perturbative calculation

- Low $q^2 \leq 6 \text{ GeV}^2$

  $\rightarrow \xi_{\perp,\parallel}$ (soft form factors)

- Large $q^2 \geq 14 \text{ GeV}^2$

  $\rightarrow f_{\perp,\parallel,0}$ (helicity form factors)

- Theory uncertainties:
  - FF from non-perturbative calculations
  - $\Lambda/m_b$ corrections ("subleading corrections")
Number of signal events in full 3 fb$^{-1}$ data sample

\[
\begin{array}{cccc}
B^0 \rightarrow K^0_S \mu^+ \mu^- & B^+ \rightarrow K^+ \mu^+ \mu^- & B^0 \rightarrow K^{*0} \mu^+ \mu^- & B^+ \rightarrow K^{*+} \mu^+ \mu^- \\
N_{\text{sig}} & 176 \pm 17 & 4746 \pm 81 & 2361 \pm 56 & 162 \pm 16
\end{array}
\]

Normalise with respect to $B^0 \rightarrow J/\psi K^0_S (K^{*0})$ and $B^+ \rightarrow J/\psi K^+ (K^{*+})$

Differential branching fractions

Compatible with but lower than SM predictions


Lattice: [R. Horgan et al., PRD 89 (2014) 094501] [C. Bouchard et al., PRD 88 (2013) 054509]

\[
dB(B^0 \rightarrow K^{*0} \mu^+ \mu^-)/dq^2 \text{ with } 3 \text{ fb}^{-1} \text{ in preparation}
\]
Number of signal events in full 3 fb\(^{-1}\) data sample

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Number of Events (±Error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^0 \rightarrow K^0 \mu^+ \mu^-)</td>
<td>176 ± 17</td>
</tr>
<tr>
<td>(B^+ \rightarrow K^{+} \mu^+ \mu^-)</td>
<td>4746 ± 81</td>
</tr>
<tr>
<td>(B^0 \rightarrow K^{*0} \mu^+ \mu^-)</td>
<td>2361 ± 56</td>
</tr>
<tr>
<td>(B^+ \rightarrow K^{*+} \mu^+ \mu^-)</td>
<td>162 ± 16</td>
</tr>
</tbody>
</table>

Normalise with respect to \(B^0 \rightarrow J/\psi K^0_S(K^{*0})\) and \(B^+ \rightarrow J/\psi K^+(K^{*+})\)

Differential branching fractions

Compatible with but lower than SM predictions

Light cone sum rules (LCSR):

- P. Ball et al., PRD 71 (2005) 014029
- A. Khodjamirian et al., JHEP 09 (2010) 089

Lattice:

- R. Horgan et al., PRD 89 (2014) 094501
- C. Bouchard et al., PRD 88 (2013) 054509

\(d\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)/dq^2\) with 3 fb\(^{-1}\) in preparation
Branching fraction and $K^+\pi^-$ S-wave from $(m_{K\pi\mu\mu}, m_{K\pi}, \cos \theta_K)$ fit

Measurement relative to normalisation mode $B^0 \rightarrow J/\psi K^{*0}$

$$\frac{dB(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{dq^2} = \frac{1}{q^2_{\text{max.}} - q^2_{\text{min.}}} \times \frac{1 - F^{K^*\mu\mu}_S}{1 - F^{J/\psi K^*}_S} \times \frac{N_{K^*\mu\mu}}{N_{J/\psi K^*}} \times \frac{\epsilon_{K^*\mu\mu}}{\epsilon_{J/\psi K^*}} \times B(B^0 \rightarrow J/\psi K^{*0}) \times B(J/\psi \rightarrow \mu^+ \mu^-)$$

$\frac{\epsilon_{K^*\mu\mu}}{\epsilon_{J/\psi K^*}}$ from (corrected) simulation, many effects cancel in ratio
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ branching fraction result

■ Good agreement with but slightly lower than SM prediction

[JHEP (2016) 98] [PRD 89 (2014) 094501]

■ Most precise measurement of total branching fraction

$$\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-) = (0.904^{+0.016}_{-0.015} \pm 0.010 \pm 0.006 \pm 0.061) \times 10^{-6}$$
The rare decay $B^0_s \rightarrow \phi [\rightarrow K^+ K^-] \mu^+ \mu^-$

- Dominant $b \rightarrow s \mu^+ \mu^-$ decay for $B^0_s$, analogous to $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- $\phi (\rightarrow K^+ K^-) \mu^+ \mu^-$ final state not flavour specific
  $\rightarrow$ reduced number of observables 4 CP averages, 4 CP asymmetries

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/d^2q} \frac{d^3(\Gamma + \bar{\Gamma})}{d\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell 
- F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi 
+ S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + A_5 \sin 2\theta_K \sin \theta_\ell \cos \phi 
+ A_6 \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi 
+ A_8 \sin 2\theta_K \sin \theta_\ell \sin \phi + A_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]
\]

- Signal yield lower due to $\frac{f_s}{f_d} \sim \frac{1}{4}$, $\frac{B(\phi \rightarrow K^+ K^-)}{B(K^{*0} \rightarrow K^+ \pi^-)} = \frac{3}{4}$

- Clean selection due to narrow $\phi$ resonance
The $B_s^0 \to \phi \mu^+ \mu^-$ signal decay

- Suppression of combinatorial background with BDT, peaking backgrounds with PID and kinematic quantities
- Veto $q^2$ range $[8, 11] \cup [12.5, 15]$ GeV$^2$/c$^4$ containing tree level decays $B_s^0 \to J/\psi \phi$ and $B_s^0 \to \psi(2S)\phi$ (important control modes)
- Signal clearly visible as vertical band after the full selection
Good agreement of angular obs. with SM predictions
Good agreement of angular obs. with SM predictions
Branching fraction determined relative to $B_s^0 \rightarrow J/\psi \phi$

$$\frac{dB(B_s^0 \rightarrow \phi \mu^+ \mu^-)}{dq^2} = \frac{1}{q_{\text{max}}^2 - q_{\text{min}}^2} \times \frac{N_{\phi \mu \mu}}{N_{J/\psi \phi}} \times \frac{\epsilon_{\phi \mu \mu}}{\epsilon_{J/\psi \phi}} \times B(B_s^0 \rightarrow J/\psi \phi) \times B(J/\psi \rightarrow \mu^+ \mu^-)$$

$\frac{\epsilon_{\phi \mu \mu}}{\epsilon_{J/\psi \phi}}$ from (corrected) simulation, many effects cancel in ratio

$K^+ K^-$ S-wave negligible due to narrow $\phi$ resonance
The anomalies | Tests of lepton universality

$B^0_s \rightarrow \phi \mu^+ \mu^-$ branching fraction

- In $1 < q^2 < 6 \text{GeV}^2/c^4$ dif. $B$ more than $3 \sigma$ below SM prediction
- Confirming deviation seen in $1 \text{fb}^{-1}$ analysis [JHEP 07 (2013) 084]
- Most precise measurement of relative and total branching fraction

$$\frac{\mathcal{B}(B^0_s \rightarrow \phi \mu^+ \mu^-)}{\mathcal{B}(B^0_s \rightarrow J/\psi \phi)} = (7.41^{+0.42}_{-0.40} \pm 0.20 \pm 0.21) \times 10^{-4},$$

$$\mathcal{B}(B^0_s \rightarrow \phi \mu^+ \mu^-) = (7.97^{+0.45}_{-0.43} \pm 0.22 \pm 0.23 \pm 0.60) \times 10^{-7},$$
Trigger for electron final states

- **LOE**: trigger fired on one of the electrons
- **LOH**: trigger fired on the final state hadron(s)
- **LOI**: trigger fired by other particles in the event

- Calorimeter occupancy high:
  - Trigger thresholds for electron final states higher than for muons

<table>
<thead>
<tr>
<th>$p_T$ threshold (Run 1)</th>
<th>muons</th>
<th>electrons</th>
<th>hadrons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.5 – 1.8 GeV</td>
<td>2.5 – 3.0 GeV</td>
<td>3.5 GeV</td>
</tr>
</tbody>
</table>

- Combination of different triggers used to increase yields
- Using exclusive trigger categories: Different resolutions/purities
Crosschecks

- $r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+ \mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+ e^-))} = 1.043 \pm 0.006 \pm 0.045$
  - Compatible with unity, ind. of decay kinematics, event multiplicity
  - Residual non-flatness accounted in $R_{K^*}$ systematics
  - Extremely stringent test, not a double ratio

- $\mathcal{B}(B^0 \to K^{*0} \mu^+ \mu^-)$ in good agreement with [JHEP 04 (2017) 142]

- $R_{\psi(2S)} = \frac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to \mu^+ \mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+ \mu^-))} / \frac{\mathcal{B}(B^0 \to K^{*0} \psi(2S)(\to e^+ e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+ e^-))}$,
  - $R_{\gamma} = \frac{\mathcal{B}(B^0 \to K^{*0} \gamma(\to e^+ e^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+ e^-))}$
  - compatible with expectations

- Neglecting corrections to simulation, $R_{K^*}$ changes by less than 5%
### Systematic uncertainties

<table>
<thead>
<tr>
<th></th>
<th>$\Delta R_{K^*0}/R_{K^*0}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low-$q^2$</td>
</tr>
<tr>
<td><strong>Trigger category</strong></td>
<td></td>
</tr>
<tr>
<td>L0E</td>
<td></td>
</tr>
<tr>
<td>L0H</td>
<td></td>
</tr>
<tr>
<td>L0I</td>
<td></td>
</tr>
<tr>
<td><strong>Corrections to simulation</strong></td>
<td>2.5</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.1</td>
</tr>
<tr>
<td>PID</td>
<td>0.2</td>
</tr>
<tr>
<td>Kinematic selection</td>
<td>2.1</td>
</tr>
<tr>
<td>Residual background</td>
<td>–</td>
</tr>
<tr>
<td>Mass fits</td>
<td>1.4</td>
</tr>
<tr>
<td>Bin migration</td>
<td>1.0</td>
</tr>
<tr>
<td>$r_{J/\psi}$ ratio</td>
<td>1.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>4.0</td>
</tr>
</tbody>
</table>

- Many systematic effects cancel in the double-ratio
- Measurement statistically dominated ($\sigma_{stat} \sim 16\%$)

bremsstrahlung tail description
residual bkgs. from $B^0 \rightarrow K^{*0} J/\psi (ee)$ with $h \leftrightarrow e$ swap
LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures

- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu\mu$
- 150 kHz $e/\gamma$

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

2-5 GB/s to storage

C. Langenbruch (RWTH), QCD@LHC

The anomalies | Tests of lepton universality
# LHCb prospects for Run 2 and the upgrade

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHC Run 1</th>
<th>LHCb 2018</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$\phi_s(B_s^0 \to J/\psi \phi) \text{ (rad)}$</td>
<td>0.049</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$\phi_s(B_s^0 \to J/\psi f_0(980)) \text{ (rad)}$</td>
<td>0.068</td>
<td>0.035</td>
<td>0.012</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$A_{s1}(B_s^0) (10^{-3})$</td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>0.03</td>
</tr>
<tr>
<td>Gluonic penguin</td>
<td>$\phi_s^{\text{eff}}(B_s^0 \to \phi \phi) \text{ (rad)}$</td>
<td>0.15</td>
<td>0.10</td>
<td>0.018</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$\phi_s^{\text{eff}}(B_s^0 \to K^{*0} K^{*0}) \text{ (rad)}$</td>
<td>0.19</td>
<td>0.13</td>
<td>0.023</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta^{\text{eff}}(B_s^0 \to \phi K^{0}) \text{ (rad)}$</td>
<td>0.30</td>
<td>0.20</td>
<td>0.036</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$\phi_s^{\text{eff}}(B_s^0 \to \phi \gamma) \text{ (rad)}$</td>
<td>0.20</td>
<td>0.13</td>
<td>0.025</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau^{\text{eff}}(B_s^0 \to \phi \gamma)/\tau_{B_s^0}$</td>
<td>5%</td>
<td>3.2%</td>
<td>0.6%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak penguin</td>
<td>$S_3(B^0 \to K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$q^2 A_{FB}(B^0 \to K^{*0} \mu^+ \mu^-)$</td>
<td>10%</td>
<td>5%</td>
<td>1.9%</td>
<td>$\sim 7%$</td>
</tr>
<tr>
<td></td>
<td>$A_{1}(K \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.09</td>
<td>0.05</td>
<td>0.017</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \to \pi^+ \mu^+ \mu^-)/B(B^+ \to K^+ \mu^+ \mu^-)$</td>
<td>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$B(B_s^0 \to \mu^+ \mu^-) (10^{-9})$</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>$B(B^0 \to \mu^+ \mu^-)/B(B_s^0 \to \mu^+ \mu^-)$</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>$\gamma(B \to D^{(<em>)} K^{(</em>)})$</td>
<td>7°</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma(B_s^0 \to D_s^{(<em>)} K^{(</em>)})$</td>
<td>17°</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td>angles</td>
<td>$\beta(B_s^0 \to J/\psi K_s^0)$</td>
<td>1.7°</td>
<td>0.8°</td>
<td>0.31°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_T(B^0 \to K^+ K^-) (10^{-4})$</td>
<td>3.4</td>
<td>2.2</td>
<td>0.4</td>
<td>–</td>
</tr>
<tr>
<td>$CP$ violation</td>
<td>$\Delta A_{CP} (10^{-3})$</td>
<td>0.8</td>
<td>0.5</td>
<td>0.1</td>
<td>–</td>
</tr>
</tbody>
</table>

[**LHCb-PUB-2014-040**]

**C. Langenbruch (RWTH), QCD@LHC**
Table 10.1: Summary of prospects for future measurements of selected flavour observables. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. Unless indicated otherwise the Belle-II sensitivities are taken from Ref. [568].

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current LHCb</th>
<th>LHCb 2025</th>
<th>Belle II</th>
<th>Upgrade II</th>
<th>GPDs Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EW Penguins</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R_K$ ($1 &lt; q^2 &lt; 6 \text{GeV}^2 c^4$)</td>
<td>0.1 [255]</td>
<td>0.022</td>
<td>0.036</td>
<td>0.006</td>
<td>–</td>
</tr>
<tr>
<td>$R_{K^*}$ ($1 &lt; q^2 &lt; 6 \text{GeV}^2 c^4$)</td>
<td>0.1 [254]</td>
<td>0.029</td>
<td>0.032</td>
<td>0.008</td>
<td>–</td>
</tr>
<tr>
<td>$R_\phi, R_{pK}, R_\pi$</td>
<td>–</td>
<td>0.07, 0.04, 0.11</td>
<td>–</td>
<td>0.02, 0.01, 0.03</td>
<td>–</td>
</tr>
<tr>
<td><strong>CKM tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma$, with $B_s^0 \to D_s^+ K^-$</td>
<td>$^{+17}_{-22}$° [123]</td>
<td>4°</td>
<td>–</td>
<td>1°</td>
<td>–</td>
</tr>
<tr>
<td>$\gamma$, all modes</td>
<td>$^{+5.0}_{-5.8}$° [152]</td>
<td>1.5°</td>
<td>1.5°</td>
<td>0.35°</td>
<td>–</td>
</tr>
<tr>
<td>$\sin 2\beta$, with $B^0 \to J/\psi K^0_s$</td>
<td>0.04 [569]</td>
<td>0.011</td>
<td>0.005</td>
<td>0.003</td>
<td>–</td>
</tr>
<tr>
<td>$\phi_s, B^0 \to J/\psi \phi$</td>
<td>49 mrad [32]</td>
<td>14 mrad</td>
<td>–</td>
<td>4 mrad</td>
<td>22 mrad [570]</td>
</tr>
<tr>
<td>$\phi_s, B_s^0 \to D_s^+ D_s^-$</td>
<td>170 mrad [37]</td>
<td>35 mrad</td>
<td>–</td>
<td>9 mrad</td>
<td>–</td>
</tr>
<tr>
<td>$\phi_s, B_s \to J/\psi K^0_s$</td>
<td>–</td>
<td>150 mrad [571]</td>
<td>60 mrad</td>
<td>–</td>
<td>17 mrad</td>
</tr>
<tr>
<td>$a_s^{\phi_s}$, with $B_s^0 \to D_s^+ D_s^-$</td>
<td>33 $\times 10^{-4}$ [193]</td>
<td>10 $\times 10^{-4}$</td>
<td>–</td>
<td>3 $\times 10^{-4}$</td>
<td>–</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
<td>$</td>
<td>6% [186]</td>
</tr>
<tr>
<td>$B_s^0, B_s^0 \to \mu^+ \mu^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B_s^0 \to \mu^+ \mu^-)/B(B_s^0 \to \mu^+ \mu^-)$</td>
<td>90% [244]</td>
<td>34%</td>
<td>–</td>
<td>10%</td>
<td>21% [573]</td>
</tr>
<tr>
<td>$\tau_{B_s^0 \to \mu^+ \mu^-}$</td>
<td>22% [244]</td>
<td>8%</td>
<td>–</td>
<td>2%</td>
<td>–</td>
</tr>
<tr>
<td>$S_{\mu \mu}$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.2</td>
</tr>
<tr>
<td>$b \to c \ell^- \bar{\nu}_\ell$ <strong>LUV studies</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(D^+)$</td>
<td>9% [199, 202]</td>
<td>3%</td>
<td>2%</td>
<td>1%</td>
<td>–</td>
</tr>
<tr>
<td>$R(J/\psi)$</td>
<td>25% [202]</td>
<td>8%</td>
<td>–</td>
<td>–</td>
<td>2%</td>
</tr>
<tr>
<td><strong>Charm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta A_{CP}(K K^0 - \pi \pi)$</td>
<td>$8.5 \times 10^{-4}$ [574]</td>
<td>$1.7 \times 10^{-4}$</td>
<td>$5.4 \times 10^{-4}$</td>
<td>$3.0 \times 10^{-5}$</td>
<td>–</td>
</tr>
<tr>
<td>$A_F (\approx x \sin \phi)$</td>
<td>$2.8 \times 10^{-4}$ [222]</td>
<td>$4.3 \times 10^{-5}$</td>
<td>$3.5 \times 10^{-5}$</td>
<td>$1.0 \times 10^{-5}$</td>
<td>–</td>
</tr>
<tr>
<td>$x \sin \phi$ from $D^0 \to K^+ \pi^-$</td>
<td>$13 \times 10^{-4}$ [210]</td>
<td>$3.2 \times 10^{-4}$</td>
<td>$4.6 \times 10^{-4}$</td>
<td>$8.0 \times 10^{-5}$</td>
<td>–</td>
</tr>
<tr>
<td>$x \sin \phi$ from multibody decays</td>
<td>–</td>
<td>$(K3\pi) 4.0 \times 10^{-5}$</td>
<td>$(K_s^0 \pi \pi) 1.2 \times 10^{-4}$</td>
<td>$(K3\pi) 8.0 \times 10^{-6}$</td>
<td>–</td>
</tr>
</tbody>
</table>
\( Z' \) models

- Masses typically heavy \( m_{Z'} \sim \mathcal{O}(\text{TeV}) \) but on-shell light also possible \( 100 \text{ MeV} < m_{Z'} < m_b \)

- Other constraints:
  - \( B_s^0 \) mixing \( g_{bsZ'}/m_{Z'} \lesssim 0.01/2.5 \text{ TeV} \)
  - Direct searches \( Z' \rightarrow \mu^+\mu^- \)
    - \( m_{Z'} < 3.5 \text{ TeV} \): must suppress coupling to light quark \( q \)
    - Direct searches also sensitive to tails of distributions
  - Neutrino trident production
Leptoquark models

Models generally predict $C_9^\mu = -C_{10}^\mu$

LQ masses typically $\mathcal{O}(10 \text{ TeV})$ @ tree-level, $\mathcal{O}(1 \text{ TeV})$ @ loop-level

Other constraints:

- Constraints from $B_s^0$ mixing at loop-level
- Limits from direct searches $\mathcal{O}(1 \text{ TeV})$

<table>
<thead>
<tr>
<th>S</th>
<th>G</th>
<th>Topo.</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$(\bar{3}, 1)_{1/3}$</td>
<td>loop</td>
<td>[PRL 116 (2016) 141802]</td>
</tr>
<tr>
<td>0</td>
<td>$(\bar{3}, 3)_{1/3}$</td>
<td>tree</td>
<td>[JHEP 06 (2015) 072]</td>
</tr>
<tr>
<td>1</td>
<td>$(\bar{3}, 2)_{7/6}$</td>
<td>loop</td>
<td>[arxiv:1704.05835]</td>
</tr>
<tr>
<td>1</td>
<td>$(\bar{3}, 1)_{2/3}$</td>
<td>tree</td>
<td>[EPJC 76 (2016) 67]</td>
</tr>
<tr>
<td>1</td>
<td>$(\bar{3}, 3)_{2/3}$</td>
<td>tree</td>
<td>[PLB 755 (2016) 270]</td>
</tr>
</tbody>
</table>

$B_s^0$ mixing

Direct production

$\bar{s} \to s$
Lepton universality in semileptonic decays: $R_{D^*}$

1. $R_{D^*} = \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*-} \mu^- \bar{\nu}_\mu)} \xrightarrow{\text{SM}} 0.252 \pm 0.003$ \cite{PRD 85 (2012) 094025}

2. Clean prediction as hadronic uncertainties cancel
   Below unity in the SM due to lepton mass difference
3. LHCb performed two analyses with different $\tau$ decay modes
   1. Leptonic $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ decay \cite{PRL 115 (2015) 111803}
   2. Hadronic $\tau^- \rightarrow \pi^+ \pi^- \pi^- (\pi^0) \nu_\tau$ decays \cite{PRL 120 (2018) 171802}
4. Similar experimental challenges
   - Final state neutrinos
   - Large backgrounds from partially reconstructed and misidentified decays

<table>
<thead>
<tr>
<th>decay mode</th>
<th>$\mathcal{B}[%]$ [PDG2017]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow \mu^- \bar{\nu}<em>\mu \nu</em>\tau$</td>
<td>$17.39 \pm 0.04$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^+ \pi^- \pi^- \nu_\tau$</td>
<td>$9.31 \pm 0.05$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^+ \pi^- \pi^- \pi^0 \nu_\tau$</td>
<td>$4.62 \pm 0.05$</td>
</tr>
</tbody>
</table>
Reconstructing $\bar{B}^0 \rightarrow D^{*+} \tau^- (\rightarrow \mu^- \bar{\nu}_\mu \nu_\tau) \bar{\nu}_\tau$

- No analytic solution for $B$ momentum due to missing neutrinos
- Exploit vertexing to determine $B$ flight direction: $\frac{\vec{p}(B)}{|\vec{p}(B)|} = \frac{S\bar{V} - P\bar{V}}{|S\bar{V} - P\bar{V}|}$
- Approximate $(p_B)_z = \frac{m_B}{m_{\text{reco}}} (p_{\text{reco}})_z$ to determine $p_B$ with $\sim 18\%$ resolution
- Use $m^2_{\text{miss}} = (p_B - p_{D^*} - p_\ell)^2$, $q^2 = (p_B - P_{D^*})^2$ and $E^*_\mu$ to separate $\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$ signal from $\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu$ normalisation

<table>
<thead>
<tr>
<th>$\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$ signal</th>
<th>$\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu$ normalisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m^2_{\text{miss}} &gt; 0$</td>
<td>$m^2_{\text{miss}} = 0$</td>
</tr>
<tr>
<td>$E^*_\mu$ spectrum soft</td>
<td>$E^*_\mu$ spectrum hard</td>
</tr>
<tr>
<td>$m^2_\tau \leq q^2 \leq 10.6 \text{ GeV}^2$</td>
<td>$0 \leq q^2 \leq 10.6 \text{ GeV}^2$</td>
</tr>
</tbody>
</table>
Perform 3D binned template fit in $m_{miss}^2$, $E_\mu^*$ and $q^2$

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

$R_{D^*} = 0.336 \pm 0.027 \pm 0.030$ [PRL 115 (2015) 111803], compatible with the SM at $2.1 \sigma$

Dominant systematic uncertainty: Size of simulated samples
The anomalies | Tests of lepton universality

$R_{D^*}$ with $\tau^- \rightarrow \pi^+\pi^-\pi^-\left(\pi^0\right)\nu_\tau$

**Signal**

- $B^0 \rightarrow D^{*-}\tau^+\nu_\tau$
- $D^{*-}$
- $\pi^-$
- $K^+$
- $\pi^-$
- $\bar{D}^0$

**Background**

- $B^0 \rightarrow D^{*-}\pi^+\pi^-\pi^+X$
- $D^{*-}$
- $\pi^-$
- $K^+$
- $\pi^-$

- Normalize to well known decay $B^0 \rightarrow D^*-3\pi$ with same final state:
  
  $R_{D^*} = \kappa \times \frac{\mathcal{B}(B^0 \to D^{*-}3\pi)}{\mathcal{B}(B^0 \to D^{*-})}$ with $\kappa = \frac{\mathcal{B}(B^0 \to D^{*-}\tau^+ \to 3\pi(\pi^0)\bar{v}_\tau)\nu_\tau}{\mathcal{B}(B^0 \to D^{*-}-3\pi)}$

- $\Delta z > 4\sigma_{\Delta z}$

- Main background from hadronic $B \to D^{*3\pi X}$ decays suppressed by exploiting $\tau$ lifetime (no bkg. from $B^0 \to D^{*-}\mu^+\nu_\mu$)

- BDT to suppress $B \to DD_{(S)}X$ background

![Graph showing candidates and distributions](image-url)
3D binned template fit to $q^2$, $\tau$-lifetime and BDT output

Templates from simulation, validated using control samples

$R_{D^*} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$

stat. syst. ext. [PRL 120 (2018) 171802] $1 \sigma$ above SM

External inputs

$\mathcal{B}(B^0 \to D^{*-}3\pi) = (7.21 \pm 0.28) \times 10^{-3}$

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

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$R_{D(*)}$ combination

- Combine LHCb $R_{D*}$ measurements with $B$-factory results
- All measurements are above SM predictions
- Deviation of $R_D/R_{D*}$ combination corresponding to $\sim 4.1\sigma$
- Recent theory input slightly reduces tension [JHEP 11 (2017) 061]
Combined explanations of rare- and tree-level anomalies with Leptoquarks possible, e.g. [JHEP 11 (2017) 044]

- Perform EFT fit of couplings $C_S$ and $C_T$
- using $R_D(*)$ and $b \rightarrow s\ell\ell$ anomalies and low-energy constraints
- Single vector leptoquark ($U_1$) can explain all anomalies
- HL LHC necessary to directly probe this scenario