Flavour Physics Reach after Upgrade

Olaf Steinkamp

on behalf of the LHCb collaboration

including beauty-ful results from ATLAS and CMS
Flavour Physics

Study the properties of
the three families of quarks and leptons
and their interactions

Played a crucial role in establishing the Standard Model
Flavour Physics

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“Holy Grail” of Flavour Physics today: Search for signatures of physics Beyond the Standard Model

“Indirect Searches for New Physics”
Flavour Physics

Study the properties of the three families of quarks and leptons and their interactions

Played a crucial role in establishing the Standard Model

“Holy Grail” of Flavour Physics today: Search for signatures of physics Beyond the Standard Model

“Indirect Searches for New Physics”

@ LHC: “Flavour Physics” ≈ mostly heavy quarks “Searches for BSM physics” ≈ mostly $b$ quarks
Flavour Physics

Study the properties of the three families of quarks and leptons and their interactions

Played a crucial role in establishing the Standard Model

“Holy Grail” of Flavour Physics today: Search for signatures of physics Beyond the Standard Model

“Indirect Searches for New Physics”

Many interesting and important measurements of SM physics, but no time to discuss these here … sorry !!!
Indirect Searches For BSM Physics

Most BSM physics models predict additional heavy particles

→ Can cause additional amplitudes in processes with internal loops
Indirect Searches For BSM Physics

Most BSM physics models predict additional heavy particles

→ Can cause additional amplitudes in processes with internal loops

→ Can lead to sizeable modifications of observables

Rates, angular distributions, $CP$ violating phases

![Diagram of BSM processes]
Indirect Searches For BSM Physics

Most BSM physics models predict additional heavy particles
→ Can cause additional amplitudes in processes with internal loops
→ Can lead to sizeable modifications of observables

Rates, angular distributions, $CP$ violating phases

Goal: uncover deviations from Standard Model expectations by comparing precise measurements with precise predictions
Indirect searches can be sensitive to much higher mass scales than direct searches for heavy particles.

The pattern of observed deviations can hint at the structure of the BSM physics at work.
Upgrade

ATLAS / CMS
HL-LHC upgrades

18 May 2017
LHCP 2017 – Flavour Reach After Upgrade (10/52)
O. Steinkamp
Upgrade

LHCb upgrade

Phase-2 upgrade ~ 2030?
Upgrade

LHCb upgrade

Phase-2 upgrade ~ 2030?
“After Upgrade” ≡ after LS2 (LHC Run 3 – 4)
A collider suppression collimation
cryogenics point 4

e+e−→γ(4s)→B̄B̄ / B+B−
collect 50 ab−1 by 2025
(50 × BaBar+Belle)

[arxiv:1011.0352]
“Unitarity Triangle”: from unitarity condition of CKM matrix

All angles and sides related to observables

Over-constrained fits test Standard Model
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All angles and sides related to observables

Over-constrained fits test Standard Model

So far good consistency

Current measurement precision allows for BSM contribution at 10-20% level
CKM angle $\gamma$

“Unitarity Triangle”: from unitarity condition of CKM matrix

All angles and sides related to observables

Over-constrained fits test Standard Model

So far good consistency

Current measurement precision allows for BSM contribution at 10-20% level

Least well determined from direct measurements:

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$\gamma (\text{LHCb}) = \left(72.2^{+6.8}_{-7.3}\right)^\circ$$

[JHEP 12(2016)087]
“Unitarity Triangle”: from unitarity condition of CKM matrix

All angles and sides related to observables

Over-constrained fits test Standard Model

“Clean” measurements of $\gamma$ from

Decay rates for tree decays $B^{\pm} \rightarrow D K^{\pm}$ and $B^{0} \rightarrow D^{0} K^{*0}$

Time-dependent $CP$ asymmetry in $B_{s}^{0} \rightarrow D_{s}^{+} K^{-}$
"Unitarity Triangle": from unitarity condition of CKM matrix

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"Clean" measurements of $\gamma$ from

Decay rates for tree decays $B^{\pm} \rightarrow D K^{\pm}$ and $B^{\pm} \rightarrow D K^{\pm \ast 0}$

Time-dependent $CP$ asymmetry in $B_{s}^{0} \rightarrow D_{s}^{+} K^{-}$

Small Branching Fractions: Results limited by statistical uncertainties
"Unitarity Triangle": from unitarity condition of CKM matrix

All angles and sides related to observables

Over-constrained fits test Standard Model

LHCb expect $\sigma(\gamma) < 1^\circ$ from 50 fb$^{-1}$

Belle II expect $\sigma(\gamma) \approx 1.5^\circ$ from 50 ab$^{-1}$ ($\approx 2025$)

[18 May 2017] LHCP 2017 – Flavour Reach After Upgrade (20/52) O. Steinkamp


CP violation in $B_s^0 - \overline{B}_s^0$ mixing

CP violation from interference of box diagrams with different CKM phases

probability $B_s^0 \rightarrow \overline{B}_s^0 \neq$ probability $\overline{B}_s^0 \rightarrow B_s^0$
CP violation in $B_s^0 - \bar{B}_s^0$ mixing

CP violation from interference of box diagrams with different CKM phases

Probability $B_s^0 \to \bar{B}_s^0 \neq$ probability $\bar{B}_s^0 \to B_s^0$

Can be measured in rate asymmetry for semi-leptonic decays

$$a_{s\ell}^s \equiv \frac{\Gamma(B_s^0 \to D_s^- \mu^+ X) - \Gamma(\bar{B}_s^0 \to D_s^+ \mu^- X)}{\Gamma(B_s^0 \to D_s^- \mu^+ X) + \Gamma(\bar{B}_s^0 \to D_s^+ \mu^- X)}$$

Predicted to be very small in the Standard Model

$$a_{s\ell}^s (\text{SM}) = (1.9 \pm 0.3) \times 10^{-5}$$

Sensitive to possible BSM physics contributions in mixing
CP violation in $B_s^0 - \overline{B}_s^0$ mixing

CP violation from interference of box diagrams with different CKM phases

Probability $B_s^0 \rightarrow \overline{B}_s^0 \neq$ probability $\overline{B}_s^0 \rightarrow B_s^0$

LHCb Run 1:

$$a_{s}^{s}(\text{LHCb}) = (390 \pm 260 \pm 200) \times 10^{-5}$$

Systematics dominated by statistics in control samples
CP violation in $B_s^0 - \overline{B}_s^0$ mixing

CP violation from interference of box diagrams with different CKM phases

probability $B_s^0 \rightarrow \overline{B}_s^0 \neq$ probability $\overline{B}_s^0 \rightarrow B_s^0$

LHCb expect

$\sigma(a_{s1}^s) \approx 50 \times 10^{-5}$

from 50 fb$^{-1}$
CP violation in $B_s^0 - \bar{B}_s^0$ mixing

CP violation from interference of box diagrams with different CKM phases

probability $B_s^0 \to \bar{B}_s^0 \neq$ probability $\bar{B}_s^0 \to B_s^0$

LHCb expect

$\sigma (a_{sl}^s) \approx 50 \times 10^{-5}$

from 50 fb$^{-1}$
CP violation in $B_s^0 \rightarrow J/\psi \phi$

CP violation through interference between mixing and decay amplitudes

CP violating phase

$$\phi_s = \phi_M - 2\phi_D$$
**CP violation in $B_s^0 \to J/\psi \phi$**

**CP violation through interference between mixing and decay amplitudes**

**CP violating phase**

$$\phi_s = \phi_M - 2\phi_D$$

Predicted to be very small in the Standard Model:

- $B_s^0 - \overline{B}_s^0$ mixing phase $\phi_M$ very small (as discussed above)
- Decay amplitude dominated by a single tree diagram $\to \phi_D$ very small

$$\phi_s^{(\text{SM})} = -38 \pm 1 \text{ mrad}$$

Sensitive to possible contributions from BSM physics in $B_s^0 - \overline{B}_s^0$ mixing
**CP violation in \( B_s^0 \rightarrow J/\psi \phi \)**

**CP violation through interference between mixing and decay amplitudes**

**CP violating phase**

\[ \phi_s = \phi_M - 2\phi_D \]

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**Run-1 measurements from ATLAS, CMS and LHCb**

\[ \phi_s^{(LHCb)} = -10 \pm 39 \text{ mrad} \]

Limited by statistical uncertainty

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**[PRL 114(2015)041801]**
CP violation through interference between mixing and decay amplitudes

CP violating phase

$$\phi_s = \phi_M - 2\phi_D$$

LHCb expect

$$\sigma(\phi_s) < 10 \text{ mrad}$$

from 50 fb$^{-1}$
\( CP \) violation through interference between mixing and decay amplitudes

\( CP \) violating phase

\[ \phi_s = \phi_M - 2\phi_D \]

LHCb expect

\( \sigma \left( \phi_s \right) < 10 \text{ mrad} \)

from 50 fb\(^{-1}\)
$B_s^0 \rightarrow \mu^+ \mu^-$

Flavour-changing neutral current + helicity suppressed

$$BF_{SM} (B_s^0 \rightarrow \mu^+ \mu^-) = (3.60 \pm 0.18) \times 10^{-9}$$

Bobeth et al. [PRL 112(2014)101801]  
Altmannshofer et al. [arXiv:1702.05498]
$B_{s}^{0} \rightarrow \mu^{+} \mu^{-}$

Flavour-changing neutral current + helicity suppressed

$$\text{BF}_{\text{SM}} (B_{s}^{0} \rightarrow \mu^{+} \mu^{-}) = (3.60 \pm 0.18) \times 10^{-9}$$

Large deviations possible in some BSM models
$B_s^0 \rightarrow \mu^+ \mu^-$

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$$\text{BF}_{\text{SM}} (B_s^0 \rightarrow \mu^+ \mu^-) = (3.60 \pm 0.18) \times 10^{-9}$$

Large deviations possible in some BSM models

Measurements so far in agreement with SM predictions

All limited by statistical uncertainties
Flavour-changing neutral current + helicity suppressed

\[
\text{BF}_{\text{SM}} (B_s^0 \rightarrow \mu^+ \mu^-) = (3.60 \pm 0.18) \times 10^{-9}
\]

Large deviations possible in some BSM models

\[ \rightarrow \text{Constraints on BSM models, e.g.} \]

MSSM

U_1 Leptoquark

[arXiv:1702.05498]
\( B_s^0 \rightarrow \mu^+ \mu^- \)

Flavour-changing neutral current + helicity suppressed

\[
\text{BF}_{\text{SM}} \left( B_s^0 \rightarrow \mu^+ \mu^- \right) = (3.60 \pm 0.18) \times 10^{-9}
\]

Large deviations possible in some BSM models

\( \rightarrow \) Constraints on BSM models, e.g.

LHCb expect
\[
\sigma (\text{BF}) / \text{BF} = 5 \%
\]
from 50 fb\(^{-1}\)

[CMS-PAS-FTR-13-022]

CMS expect
\[
\sigma (\text{BF}) / \text{BF} = 12 \%
\]
from 300 fb\(^{-1}\)

[CMS-PAS-FTR-13-022]

MSSM

U\(_1\) Leptoquark

Altmannshofer et al.
[arXiv:1702.05498]
Even stronger suppression due to $V_{td} < V_{ts}$

$$BF_{SM} (B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Bobeth et al.  
[PRL 112(2014)101801]
Even stronger suppression due to $V_{td} < V_{ts}$

$$BF_{SM} (B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Not observed yet

Goal for upgrade: measure the ratio of the Branching Fractions

(\text{theory uncertainty} \approx 5 \%) 

LHCb expect

$$\sigma \left( \frac{BF (B^0 \rightarrow \mu^+ \mu^-)}{BF (B_s^0 \rightarrow \mu^+ \mu^-)} \right) \approx 40 \%$$

from 50 fb$^{-1}$

[\text{LHCb-PUB-2014-040}]

CMS expect

$$\sigma \left( \frac{BF (B^0 \rightarrow \mu^+ \mu^-)}{BF (B_s^0 \rightarrow \mu^+ \mu^-)} \right) \approx 47 \%$$

from 300 fb$^{-1}$

(21 \% from 3000 fb$^{-1}$)

[CMS-PAS-FTR-13-022]
Flavour-Changing Neutral Current Decay

Angular distributions of final-state particles sensitive to possible contributions from BSM physics

\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \]
Flavour-Changing Neutral Current Decay

Angular distributions of final-state particles sensitive to possible contributions from BSM physics

Eight independent angular observables

LHCb find deviation in the central $q^2$ region for the observable $P'_5$

Local significance $\approx 3.6 \sigma$ from LHCb Run 1
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

Flavour-Changing Neutral Current Decay

Angular distributions of final-state particles sensitive to possible contributions from BSM physics

ATLAS, CMS, Belle follow up, but uncertainties larger than in LHCb
Flavour-Changing Neutral Current Decay

Angular distributions of final-state particles sensitive to possible contributions from BSM physics

ATLAS, CMS, Belle follow up, but uncertainties larger than in LHCb

LHCb expect to reduce uncertainties by \( \approx \) factor 2 by the end of Run 2
Flavour-Changing Neutral Current Decay

Angular distributions of final-state particles sensitive to possible contributions from BSM physics

ATLAS, CMS, Belle follow up, but uncertainties larger than in LHCb

LHCb expect to reduce uncertainties by ≈ factor 2 by the end of Run 2

We should be able to know then, whether this is just another statistical fluctuation
Flavour-Changing Neutral Current Decay

Angular distributions of final-state particles sensitive to possible contributions from BSM physics

If the deviation is “real”: 

$B^0 \rightarrow K^{*0} \mu^+ \mu^-$
Flavour-Changing Neutral Current Decay

Angular distributions of final-state particles sensitive to possible contributions from BSM physics

If the deviation is “real”:

With 50 fb$^{-1}$, LHCb should be able to perform unbinned amplitude fits over the full $q^2$ range and distinguish between the two hypotheses

[N.Serra, priv.comm.]
$R_K', R_{K^*}$

Testing Lepton Flavour Universality:

$$R \equiv \frac{\Gamma(b \rightarrow s \mu^+ \mu^-)}{\Gamma(b \rightarrow s e^+ e^-)}$$

expected to be very close to unity

(after phase-space correction)
Testing Lepton Flavour Universality:

\[ R \equiv \frac{\Gamma(b \rightarrow s \mu^+ \mu^-)}{\Gamma(b \rightarrow s e^+ e^-)} \]

expected to be very close to unity

LHCb find 2.6 \( \sigma \) tension in central \( q^2 \) bin for

\[ R_K \equiv \frac{\Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\Gamma(B^+ \rightarrow K^+ e^+ e^-)} \]
$R_K, \ R_{K^*}$

Testing Lepton Flavour Universality:

$$R \equiv \frac{\Gamma(b \to s \mu^+ \mu^-)}{\Gamma(b \to s e^+ e^-)}$$

expected to be very close to unity

LHCb find 2.2-2.5 $\sigma$ tension in low and central $q^2$ bins for

$$R_{K^*} \equiv \frac{\Gamma(B^0 \to K^{*0} \mu^+ \mu^-)}{\Gamma(B^0 \to K^{*0} e^+ e^-)}$$
Another test of Lepton Flavour Universality:

\[ R(D^*) \equiv \frac{\Gamma(B \to D^{(*)}\tau^+\nu_\tau)}{\Gamma(B \to D^{(*)}\mu^+\nu_\mu)} \]
Another test of Lepton Flavour Universality:

\[ R(D^{(*)}) \equiv \frac{\Gamma(B \to D^{(*)} \tau^+ \nu_\tau)}{\Gamma(B \to D^{(*)} \mu^+ \nu_\mu)} \]

BaBar and Belle find both \( R(D^*) \) and \( R(D) \) larger than predicted.

LHCb also find 2.1 \( \sigma \) tension for \( R(D^*) \), using \( \tau \to \mu \nu_\mu \nu_\tau \).

\( R(D^*), R(D) \) combined: 3.9 \( \sigma \) tension.
Another test of Lepton Flavour Universality:

\[
R(D^{(*)}) \equiv \frac{\Gamma(B \rightarrow D^{(*)}\tau^+\nu_{\tau})}{\Gamma(B \rightarrow D^{(*)}\mu^+\nu_{\mu})}
\]

Other LHCb analyses underway, e.g.

- \(R(D^*)\) using \(\tau \rightarrow \pi \pi \pi \nu_{\tau}\)
- \(R(D), R(D_s^{(*)}), R(J/\psi), R(\Lambda_c)\)

With upgrade statistics, might become sensitive to angular distributions
Summary

Holy Grail of Flavour Physics

= “Indirect” Searches for BSM Physics

“Classic” benchmark observables so far in agreement with SM predictions

Measurement uncertainties limited by statistics and much larger than those on theory

→ Expect significant improvements from upgrades

Some intriguing deviations in observables testing Lepton Flavour Universality

Again, measurements limited by statistical uncertainties
Upgrade statistics will help to show, whether these are fluke coincidences or part of a consistent pattern
Summary

Holy Grail of Flavour Physics

= “Indirect” Searches for BSM Physics

These Indirect Searches need to be complemented by Direct Searches at the “Energy Frontier”

(e.g. \(Z' \rightarrow \tau^+\tau^-\))

Close interaction between Experimentalists and Theorists is mandatory to derive consistent interpretation of data, to develop new observables

Again, measurements limited by statistical uncertainties Upgrade statistics will help to show, whether these are fluke coincidences or part of a consistent pattern
Summary

What if, by the end of Run 2, …

… BSM signal is found in “direct searches”

→ Precision measurements
to characterize the flavour structure of the BSM physics

… BSM signal is found in “indirect searches”

→ Follow-up measurements

… no clear signal for BSM physics found anywhere

→ Continue to push highest mass scales with precision flavour measurements
Backup
### Prospects @ LHCb

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHCb 2018</th>
<th>Upgrade (50 fb⁻¹)</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$2\beta_s (B_s^0 \rightarrow J/\psi \phi)$</td>
<td>0.025</td>
<td>0.008</td>
<td>~0.003</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s (B_s^0 \rightarrow J/\psi f_0(980))$</td>
<td>0.045</td>
<td>0.014</td>
<td>~0.01</td>
</tr>
<tr>
<td></td>
<td>$\alpha_{s1}$</td>
<td>0.6 x 10⁻³</td>
<td>0.2 x 10⁻³</td>
<td>0.03 x 10⁻³</td>
</tr>
<tr>
<td>Gluonic penguins</td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi \phi)$</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow K^{*0} K^{*0})$</td>
<td>0.13</td>
<td>0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi K_S^0)$</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi \gamma)$</td>
<td>0.09</td>
<td>0.02</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td></td>
<td>$\tau^{\text{eff}} (B_s^0 \rightarrow \phi \gamma)/\tau_{B_s^0}$</td>
<td>5 %</td>
<td>1 %</td>
<td>0.2 %</td>
</tr>
<tr>
<td>Electroweak penguins</td>
<td>$S_3 (B^0 \rightarrow K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$s_0 A_{FB} (B^0 \rightarrow K^{*0} \mu^+ \mu^-)$</td>
<td>6 %</td>
<td>2 %</td>
<td>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>0.08</td>
<td>0.025</td>
<td>~0.02</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \rightarrow \pi^+ \mu^+ \mu^-)/B(B^+ \rightarrow K^+ \mu^+ \mu^-)$</td>
<td>8 %</td>
<td>2.5 %</td>
<td>~10 %</td>
</tr>
<tr>
<td>Higgs penguins</td>
<td>$B(B_s^0 \rightarrow \mu^+ \mu^-)$</td>
<td>0.5 x 10⁻⁹</td>
<td>0.15 x 10⁻⁹</td>
<td>0.3 x 10⁻⁹</td>
</tr>
<tr>
<td></td>
<td>$B(B^0 \rightarrow \mu^+ \mu^-)/B(B_s^0 \rightarrow \mu^+ \mu^-)$</td>
<td>~100 %</td>
<td>~35 %</td>
<td>~5 %</td>
</tr>
<tr>
<td>Unitarity triangle angles</td>
<td>$\gamma (B \rightarrow D^{(<em>)} K^{(</em>)})$</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma (B_s^0 \rightarrow D_s K)$</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta (B^0 \rightarrow J/\psi K_S^0)$</td>
<td>0.6°</td>
<td>0.2°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm CP violation</td>
<td>$A_T$</td>
<td>0.40 x 10⁻³</td>
<td>0.07 x 10⁻³</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>$\Delta A_{CP}$</td>
<td>0.65 x 10⁻³</td>
<td>0.12 x 10⁻³</td>
<td>–</td>
</tr>
</tbody>
</table>
### Prospects LFU@LHCb

<table>
<thead>
<tr>
<th>Observable</th>
<th>Run 1 result</th>
<th>$8 \text{ fb}^{-1}$</th>
<th>$50 \text{ fb}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield $B^0 \to K^{*0} \mu^+ \mu^-$</td>
<td>2398 ± 57</td>
<td>9175</td>
<td>70480</td>
</tr>
<tr>
<td>Yield $B_s^0 \to \phi \mu^+ \mu^-$</td>
<td>432 ± 24</td>
<td>1653</td>
<td>12697</td>
</tr>
<tr>
<td>Yield $B^+ \to K^+ \mu^+ \mu^-$</td>
<td>4746 ± 81</td>
<td>18159</td>
<td>139491</td>
</tr>
<tr>
<td>Yield $B^+ \to \pi^+ \mu^+ \mu^-$</td>
<td>93 ± 12</td>
<td>355</td>
<td>2725</td>
</tr>
<tr>
<td>Yield $\Lambda^0_b \to \Lambda \mu^+ \mu^-$</td>
<td>373 ± 25</td>
<td>1426</td>
<td>10957</td>
</tr>
<tr>
<td>Yield $B^+ \to K^+ e^+ e^-$ ($1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4$)</td>
<td>254 ± 29</td>
<td>972</td>
<td>7465</td>
</tr>
<tr>
<td>$d\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-, 1.0 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4)/dq^2[10^{-9} \text{ GeV}^{-2} \text{c}^4]$</td>
<td>0.91 ± 0.21</td>
<td>0.11</td>
<td>0.04</td>
</tr>
<tr>
<td>$d\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-, 15 &lt; q^2 &lt; 22 \text{ GeV}^2/\text{c}^4)/dq^2[10^{-9} \text{ GeV}^{-2} \text{c}^4]$</td>
<td>0.47 ± 0.12</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td>$A_{FB}(B^0 \to K^{*0} \mu^+ \mu^-, 1.1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4)$</td>
<td>-0.075 ± 0.034 ± 0.007</td>
<td>0.017</td>
<td>0.006</td>
</tr>
<tr>
<td>$A_{FB}(B^0 \to K^{*0} \mu^+ \mu^-, 15 &lt; q^2 &lt; 19 \text{ GeV}^2/\text{c}^4)$</td>
<td>0.355 ± 0.027 ± 0.009</td>
<td>0.014</td>
<td>0.005</td>
</tr>
<tr>
<td>$S_5(B^0 \to K^{*0} \mu^+ \mu^-, 1.1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4)$</td>
<td>-0.023 ± 0.050 ± 0.005</td>
<td>0.026</td>
<td>0.009</td>
</tr>
<tr>
<td>$S_5(B^0 \to K^{*0} \mu^+ \mu^-, 15 &lt; q^2 &lt; 19 \text{ GeV}^2/\text{c}^4)$</td>
<td>-0.325 ± 0.037 ± 0.009</td>
<td>0.019</td>
<td>0.007</td>
</tr>
<tr>
<td>$S_5(B^0 \to \bar{K}^{*0} \mu^+ \mu^-, 1.1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4)$</td>
<td>-</td>
<td>-</td>
<td>0.087</td>
</tr>
<tr>
<td>$S_5(B^0 \to \bar{K}^{*0} \mu^+ \mu^-, 15 &lt; q^2 &lt; 19 \text{ GeV}^2/\text{c}^4)$</td>
<td>-</td>
<td>-</td>
<td>0.064</td>
</tr>
<tr>
<td>$\mathcal{R}_K(1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4)$</td>
<td>0.745 ± 0.090 ± 0.036</td>
<td>0.046</td>
<td>0.017</td>
</tr>
</tbody>
</table>
Phase 1 (completed)
- Circulate beams (no collisions)

Phase 2 (2017-2018)
- First collisions
- Physics without vertex detector

Phase 3 (2018-2025)
- Physics with full detector
“Unitarity Triangle”: from unitarity condition of CKM matrix

All angles and sides related to observables

Over-constrained fits test Standard Model

“Clean” measurements of $\gamma$ through

Decay rates for tree decays $B^{\pm} \rightarrow D K^{\pm}$ and $B^b \rightarrow D K^*$

Time-dependent $CP$ asymmetry in $B_s^0 \rightarrow D_s^+ K^-$
# Systematics $a_{sl}^s$

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
<th>Statistical uncertainties</th>
<th>Systematic uncertainties</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{raw}$</td>
<td>0.11</td>
<td>0.09</td>
<td>0.02</td>
</tr>
<tr>
<td>$-A_{track}(K^+K^-)$</td>
<td>0.01</td>
<td>0.00</td>
<td>0.03</td>
</tr>
<tr>
<td>$-A_{track}(\pi^-\mu^+)$</td>
<td>0.01</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>$-A_{PID}$</td>
<td>-0.01</td>
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<td>0.03</td>
</tr>
<tr>
<td>$-A_{trig}(hardware)$</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>$-A_{trig}(software)$</td>
<td>0.00</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>$-f_{bkg} A_{bkg}$</td>
<td>0.02</td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>$(1 - f_{bkg})a_{sl}^s/2$</td>
<td>0.16</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>$2/(1 - f_{bkg})$</td>
<td>2.45</td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td>$a_{sl}^s$</td>
<td>0.39</td>
<td>0.26</td>
<td>0.20</td>
</tr>
</tbody>
</table>

$$a_{sl}^s = \left(3.9 \pm 2.6 \pm 2.0\right) \times 10^{-3}$$

---

**LHCb Run 1**

[PLR 117 (2016) 061803]
## Systematics $\phi_s$

| Source                           | $\Gamma_s$ (ps$^{-1}$) | $\Delta\Gamma_s$ (ps$^{-1}$) | $|A_\perp|^2$ | $|A_0|^2$ | $\delta_{||}$ (rad) | $\delta_\perp$ (rad) | $\phi_s$ (rad) | $|\lambda|$ | $\Delta m_s$ (ps$^{-1}$) |
|---------------------------------|-------------------------|-------------------------------|---------------|----------|---------------------|---------------------|---------------|-----------|--------------------------|
| Total statistical uncertainty   | 0.0027                  | 0.0091                        | 0.0049        | 0.0034   | $+0.10$             | $-0.17$             | $+0.14$       | 0.049     | 0.019                    | $+0.055$           | $-0.057$ |
| Mass factorization              | ...                     | 0.0007                        | 0.0031        | 0.0064   | 0.05                | 0.05                | 0.002        | 0.001     | 0.004                    |
| Signal weights (statistical)   | 0.0001                  | 0.0001                        | ...           | 0.0001   | ...                 | ...                 | ...           | ...       | ...                      |
| $b$-hadron background           | 0.0001                  | 0.0004                        | 0.0004        | 0.0002   | 0.02                | 0.02                | 0.002        | 0.003     | 0.001                    |
| $B^+_c$ feed down               | 0.0005                  | ...                           | ...           | ...      | ...                 | ...                 | ...           | ...       | ...                      |
| Angular resolution bias         | ...                     | ...                           | 0.0006        | 0.0001   | $-0.03$             | 0.01                | ...           | ...       | ...                      |
| Angular efficiency (reweighting)| 0.0001                  | ...                           | 0.0011        | 0.0020   | 0.01                | ...                 | 0.001        | 0.005     | 0.002                    |
| Angular efficiency (statistical)| 0.0001                  | 0.0002                        | 0.0011        | 0.0004   | 0.02                | 0.01                | 0.004        | 0.002     | 0.001                    |
| Decay-time resolution           | ...                     | ...                           | ...           | ...      | ...                 | 0.01                | 0.002        | 0.001     | 0.005                    |
| Trigger efficiency (statistical)| 0.0011                  | 0.0009                        | ...           | ...      | ...                 | ...                 | ...           | ...       | ...                      |
| Track reconstruction (simulation)| 0.0007                 | 0.0029                        | 0.0005        | 0.0006   | $+0.01$             | $-0.02$             | 0.002        | 0.001     | 0.006                    |
| Track reconstruction (statistical)| 0.0005                | 0.0002                        | ...           | ...      | ...                 | ...                 | 0.001        | 0.001     | 0.005                    |
| Length and momentum scales      | 0.0002                  | ...                           | ...           | ...      | ...                 | ...                 | ...           | ...       | ...                      |
| $S$-$P$ coupling factors        | ...                     | ...                           | ...           | ...      | 0.01                | 0.01                | ...           | ...       | ...                      |
| Fit bias                        | ...                     | ...                           | 0.0005        | ...      | 0.01                | ...                 | 0.001        | ...       | ...                      |
| Quadratic sum of systematics    | 0.0015                  | 0.0032                        | 0.0036        | 0.0067   | $+0.06$             | $-0.07$             | 0.006        | 0.007     | 0.011                    |

$\phi_s = -0.010 \pm 0.039 \text{ rad}$
Penguin Pollution in $J/\psi \phi$

- Penguin decay amplitude suppressed by smallness of CKM matrix element
  \[ |V_{cb}V_{cs}^*| \propto \lambda^2 \]
  \( \lambda = \sin \theta_C \approx 0.23 \)

- But effects from hadronic form factors not easy to estimate

- Derive constraints on possible penguin pollution from $B_s^0 \rightarrow J/\psi K^{*0}$ and $B^0 \rightarrow J/\psi \rho^0$, where penguin and tree amplitudes have similar magnitude

  \[ |V_{cb}V_{cd}^*| \propto \lambda^3 \]
  \[ |V_{ub}V_{us}^*| \propto \lambda^4 \]
  \[ |V_{tb}V_{td}^*| \propto \lambda^3 \]

- For $B^0 \rightarrow J/\psi \rho^0$, assume that effects from SU(3)-breaking can be neglected

18 May 2017
Penguin Pollution in J/ψ φ

- 18'000 $B^0 \rightarrow J/\psi \pi^+ \pi^-$ and 1'800 $B_s^0 \rightarrow J/\psi \bar{K}^*$ signal candidates from 3 fb$^{-1}$
- time-dependent angular analyses to extract polarisation fractions and CP asymmetries in each polarization state

$$A_{i}^{CP} = -\frac{2a_i \sin \theta_i \sin \gamma}{1-2a_i \cos \theta_i \cos \gamma + a_i^2} \quad (i \in \{0, \parallel, \perp\})$$

- derive constraints on fraction $a_i$ and strong phase $\theta_i$ of penguin contributions
- translate into constraints on phase shift on $\phi_s$
Similar to $B_s^0 \rightarrow J/\psi \phi$,
but decay amplitude dominated by penguin diagram

Sensitive to possible BSM contributions in decay
Similar to $B_s^0 \rightarrow J/\psi \phi$, but decay amplitude dominated by penguin diagram.

Sensitive to possible BSM contributions in decay.

LHCb Run-1 measurement:

$$\phi_{s}^{\phi\phi}(\text{LHCb}) = -0.17 \pm 0.15 \pm 0.03 \text{ rad}$$

[PRD 90 (2014) 052011]
**CP violation in $B_s^0 \rightarrow \phi \phi$**

Similar to $B_s^0 \rightarrow J/\psi \phi$, but decay amplitude dominated by penguin diagram

Sensitive to possible BSM contributions in decay

LHCb expect

\[ \sigma (\phi_s \phi) \approx 0.02 \text{ rad} \]

from 50 fb\(^{-1}\)
Systematics BF ($B_{s}^{0} \rightarrow \mu^{+} \mu^{-}$)

Measure BF relative to $B^{+} \rightarrow J/\psi (\mu^{+} \mu^{-}) K^{+}$ and $B^{0} \rightarrow K^{+} \pi^{-}$

$$BF \left( B_{s}^{0} \rightarrow \mu^{+} \mu^{-} \right) = BF \left( \text{ref} \right) \times \frac{N \left( B_{s}^{0} \rightarrow \mu^{+} \mu^{-} \right)}{N \left( \text{ref} \right)} \times \frac{f_{\text{ref}}}{f_{s}} \times \frac{\epsilon \left( \text{ref} \right)}{\epsilon \left( B_{s}^{0} \rightarrow \mu^{+} \mu^{-} \right)}$$

Systematic uncertainty dominated by relative uncertainty of $\approx 5.8\%$ on $f_{s} / f_{(u,d)}$

[LHCb-CONF-2013-011]

$$BF \left( B_{s}^{0} \rightarrow \mu^{+} \mu^{-} \right) = \left( 3.0 \pm 0.6^{+0.3}_{-0.2} \right) \times 10^{-9}$$

LHCb Run 1+2
[arXiv:1703.05747]
$B_s^0 \rightarrow \mu^+ \mu^-$

Upgrade statistics will also give access to additional observables, e.g.

$$A_{\Delta \Gamma} \equiv \frac{\Gamma(B_s^H \rightarrow \mu^+ \mu^-) - \Gamma(B_s^L \rightarrow \mu^+ \mu^-)}{\Gamma(B_s^H \rightarrow \mu^+ \mu^-) + \Gamma(B_s^L \rightarrow \mu^+ \mu^-)}$$

**Standard-Model:**

$$A_{\Delta \Gamma}^{SM} = 1$$
Upgrade statistics will also give access to additional observables, e.g.

\[
A_{\Delta \Gamma} \equiv \frac{\Gamma(B_s^H \rightarrow \mu^+ \mu^-) - \Gamma(B_s^L \rightarrow \mu^+ \mu^-)}{\Gamma(B_s^H \rightarrow \mu^+ \mu^-) + \Gamma(B_s^L \rightarrow \mu^+ \mu^-)}
\]

**Standard-Model:**

\[
A_{\Delta \Gamma}^{\text{SM}} = 1
\]

Extract \( A_{\Delta \Gamma} \) from measurements of the “effective lifetime”

\[
\tau_{\text{eff}} \equiv \frac{\int t \times \langle \frac{d\Gamma}{dt}(B_s^0 \rightarrow \mu^+ \mu^-) \rangle dt}{\int \langle \frac{d\Gamma}{dt}(B_s^0 \rightarrow \mu^+ \mu^-) \rangle dt}
\]

\[
\Rightarrow A_{\Delta \Gamma} = \frac{(1 - y_s^2) \tau_{\text{eff}} - (1 + y_s^2) \tau_{B_s^0}}{y_s (2\tau_{B_s^0} - (1 - y_s^2) \tau_{\text{eff}})}
\]

with \( \tau_{B_s^0} = \frac{1}{\Gamma_s} \) and \( y_s = \frac{\Delta \Gamma_s}{2\Gamma_s} \).
First proof-of-principle measurement by LHCb

\[ \tau_{\text{eff}} = 2.04 \pm 0.44 \pm 0.05 \text{ ps} \]

Compatible with \( A_{\Delta\Gamma} = 1 \) at 1 \( \sigma \), with \( A_{\Delta\Gamma} = -1 \) at 1.4 \( \sigma \)
$B^0 \rightarrow \mu^+ \mu^-$

Even stronger suppression due to $V_{td} < V_{ts}$

$\text{BF}_{\text{SM}} (B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

Not observed yet

3.0 $\sigma$ significance
from LHCb+CMS Run 1

[arxiv:1703.05747]

1.9 $\sigma$ significance
from LHCb Run 1+2

[arxiv:1703.05747]
$q^2$ Regions

- "low" $< 1$ GeV$^2$/c$^4$
- "central" 1–8 GeV$^2$/c$^4$
- "high" $> 14$ GeV$^2$/c$^4$

$C_7^{(i)}C_9^{(i)}$ interference

$4\left[m(\mu)^2\right]$

$\frac{d\Gamma}{dq^2}$

$J/\psi(1S')$

$\psi(2S')$

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

Long distance contributions from $c\bar{c}$ above open charm threshold

$q^2$
# Systematics $P_5'$

<table>
<thead>
<tr>
<th>Source</th>
<th>$F_L$</th>
<th>$S_{3-9}$</th>
<th>$A_{3-9}$</th>
<th>$P_1 - P_8'$</th>
<th>$q_0^2$ GeV$^2$/c$^4$</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>
<td>0.01</td>
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<tr>
<td>Acceptance polynomial order</td>
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<td>&lt; 0.02</td>
<td>&lt; 0.04</td>
<td>0.01–0.03</td>
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<tr>
<td>Data-simulation differences</td>
<td>0.01–0.02</td>
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<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.02</td>
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<tr>
<td>Acceptance variation with $q^2$</td>
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<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>—</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>
<td>&lt; 0.01</td>
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<tr>
<td>Background model</td>
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<td>&lt; 0.01</td>
<td>&lt; 0.01</td>
<td>&lt; 0.02</td>
<td>0.01–0.05</td>
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<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>
<td>0.01–0.04</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>
<td>&lt; 0.01</td>
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<tr>
<td>Det. and prod. asymmetries</td>
<td>—</td>
<td>—</td>
<td>&lt; 0.01</td>
<td>&lt; 0.02</td>
<td>—</td>
</tr>
</tbody>
</table>

\[ P_5' \left( 1.1 < q^2 < 6 \text{ GeV}^2/c^4 \right) = -0.049^{+0.107}_{-0.108} \pm 0.014 \text{ rad} \]
b → sμ⁺μ⁻ Branching Fractions

LHCb measure differential Branching Fractions as function of $q^2$: consistently lower than predicted in the central $q^2$ region?

$L H C b \rightarrow K^+ μ^+ μ^−$

$L H C b \rightarrow K^0* μ^+ μ^−$

$L H C b \rightarrow Φ μ^+ μ^−$

$L H C b \rightarrow Λ μ^+ μ^−$
**LHCb measure differential Branching Fractions as function of $q^2$: consistently lower than predicted in the central $q^2$ region?**

$b \rightarrow s \mu^+ \mu^-$ Branching Fractions

**Significant theory uncertainties from hadronic form factors**

$LHCb$ measure differential Branching Fractions as function of $q^2$: consistently lower than predicted in the central $q^2$ region?

**显著的理论不确定性来自介子形式因子。**

- $B^+ \rightarrow K^+ \mu^+ \mu^-$
  - *LHCb Run 1* ([JHEP 06(2014)133])

- $B^0 \rightarrow K^{0*} \mu^+ \mu^-$
  - *LHCb Run 1* ([JHEP 04(2017)142])

- $B_s^0 \rightarrow \phi \mu^+ \mu^-$
  - *LHCb Run 1* ([JHEP 09(2015)179])

- $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$
  - *LHCb Run 1* ([JHEP 06(2015)115])
Systematics $R_K$

The dominant sources of systematic uncertainty are due to the parametrization of the $B^+ \rightarrow J/\psi(\rightarrow e^+e^-)K^+$ mass distribution and the estimate of the trigger efficiencies that both contribute 3% to the value of $R_K$.

$R_K \left( 1 < q^2 < 6 \text{GeV}^2/c^4 \right) = 0.745 ^{+0.090}_{-0.074} \pm 0.036$

LHCb Run 1

[PRL 113(2014)151601]
## Systematics $R_{K^*}$

<table>
<thead>
<tr>
<th>Trigger category</th>
<th>low-$q^2$</th>
<th>central-$q^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LOE</td>
<td>LOH</td>
</tr>
<tr>
<td>Corrections to simulation</td>
<td>2.5</td>
<td>4.8</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.1</td>
<td>1.2</td>
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<tr>
<td>PID</td>
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<td>0.4</td>
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<tr>
<td>Kinematic selection</td>
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<td>2.1</td>
</tr>
<tr>
<td>Residual background</td>
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<td>-</td>
</tr>
<tr>
<td>Mass fits</td>
<td>1.4</td>
<td>2.1</td>
</tr>
<tr>
<td>Bin migration</td>
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<td>1.0</td>
</tr>
<tr>
<td>$\tau_{J/\psi}$ flatness</td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Total</td>
<td>4.0</td>
<td>6.1</td>
</tr>
</tbody>
</table>

\[
R_{K^*} (0.045 < q^2 < 1.1 \text{GeV}^2/c^4) = 0.660^{+0.11}_{-0.07} \pm 0.03
\]

\[
R_{K^*} (1.1 < q^2 < 6 \text{GeV}^2/c^4) = 0.685^{+0.11}_{-0.07} \pm 0.05
\]

LHCb Run 1

[arXiv:1705.05802]
Another test of Lepton Flavour Universality:

\[ R(D^{(*)}) \equiv \frac{\Gamma(B \to D^{(*)} \tau^+ \nu_\tau)}{\Gamma(B \to D^{(*)} \mu^+ \nu_\mu)} \]

Tree decays with BF of about a percent

But \( \tau \) reconstruction challenging at hadron colliders
## Systematics $R(D^*)$

<table>
<thead>
<tr>
<th>Model uncertainties</th>
<th>Absolute size ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>2.0</td>
</tr>
<tr>
<td>Misidentified $\mu$ template shape</td>
<td>1.6</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors</td>
<td>0.6</td>
</tr>
<tr>
<td>$\bar{B} \rightarrow D^{*+} H_\epsilon (\rightarrow \mu \nu X') X$ shape corrections</td>
<td>0.5</td>
</tr>
<tr>
<td>$B(\bar{B} \rightarrow D^{<strong>} \tau^- \bar{\nu}_\tau)/B(\bar{B} \rightarrow D^{</strong>} \mu^- \bar{\nu}_\mu)$</td>
<td>0.5</td>
</tr>
<tr>
<td>$\bar{B} \rightarrow D^{**} (\rightarrow D^* \pi \pi) \mu \nu$ shape corrections</td>
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</tr>
<tr>
<td>Corrections to simulation</td>
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</tr>
<tr>
<td>Combinatorial background shape</td>
<td>0.3</td>
</tr>
<tr>
<td>$\bar{B} \rightarrow D^{**} (\rightarrow D^{*+} \pi) \mu^- \bar{\nu}_\mu$ form factors</td>
<td>0.3</td>
</tr>
<tr>
<td>$\bar{B} \rightarrow D^{*+} (D_s \rightarrow \tau \nu) X$ fraction</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total model uncertainty</strong></td>
<td><strong>2.8</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normalization uncertainties</th>
<th>Absolute size ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
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</tr>
<tr>
<td>Hardware trigger efficiency</td>
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</tr>
<tr>
<td>Particle identification efficiencies</td>
<td>0.3</td>
</tr>
<tr>
<td>Form-factors</td>
<td>0.2</td>
</tr>
<tr>
<td>$B(\tau^- \rightarrow \mu^- \bar{\nu}<em>\mu \nu</em>\tau)$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td><strong>Total normalization uncertainty</strong></td>
<td><strong>0.9</strong></td>
</tr>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td><strong>3.0</strong></td>
</tr>
</tbody>
</table>

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

LHCb Run 1  
[PRL 115(2015)111803]
$B^0 \rightarrow K^{*0} \ell^+ \ell^-$

**Graph:**

- **SM from DHMV**
- **LHCb Run 1 analysis**
- **Belle $e^+e^-$ arXiv:1612.05014**
- **Belle $\mu^+\mu^-$ arXiv:1612.05014**

**Axes:**
- $P_5'$
- $q^2$ [GeV$^2$/c$^4$]

**References:**
- [LHCb Run 1](JHEP 02(2016)104)
- [Belle](PRL 118(2017)111801)

18 May 2017

LHCP 2017 – Flavour Reach After Upgrade (79/52)

O. Steinkamp
Long standing discrepancies between exclusive and inclusive determinations of $V_{ub}$ and $V_{cb}$

Inclusive analyses assume LFU to estimate backgrounds from BF ($b \rightarrow X_{u,c} \tau \nu_{\tau}$)

Taking central values from $R(D)$ and $R(D^*)$ measurements:

$\text{BF} (b \rightarrow X_{u,c} \tau \nu_{\tau}) \approx 20 \%$ larger than expected from LFU
Taking into account up to 90 observables from different experiments, including $B \rightarrow \mu \mu$ and $b \rightarrow s \ell \ell$ transitions