Flavour anomalies in B-physics

Nico Serra (Universität Zürich) on behalf of the LHCb collaboration

Phenomenology Symposium 2019

University of Pittsburg 6-8th May
• $b\bar{b}$ produced predominantly forward and backward
• Displacement between primary (PV) and secondary (SV) vertexes one of the main discriminating variable
• Run 1 LHCb collected 1+2 fb$^{-1}$ of data in 2011+2012
• Run 2 LHCb collected 6 fb$^{-1}$ of data between 2015 and 2018 (roughly twice $b$-meson per fb$^{-1}$ due to increased $\sqrt{s}$)
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• Run 1 LHCb collected 1+2 fb$^{-1}$ of data in 2011+2012
• Run 2 LHCb collected 6 fb$^{-1}$ of data between 2015 and 2018 (roughly twice $b$-meson per fb$^{-1}$ due to increased $\sqrt{s}$)
Use an effective operator approach, similar to Fermi theory of weak interaction

\[ \mathcal{A}(i \rightarrow f) = \langle f | \mathcal{H}_{\text{eff}} | i \rangle \]
Effective Hamiltonian

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

有效的哈密顿量

局域操作符

\[ \langle f | O_i | i \rangle \] 长距离QCD

新物理可以贡献不同的WCs，取决于其洛伦兹结构

\[ \mathcal{O}_9^{()} \propto \left( \bar{s} \gamma_\mu P_{R(L)} b \right) \left( \bar{\ell} \gamma^\mu \ell \right) \]

\[ \mathcal{O}_7^{()} \propto \left( \bar{s} \sigma_{\mu\nu} P_{R(L)} b \right) F_{\mu\nu} \]

\[ \mathcal{O}_{10}^{()} \propto \left( \bar{s} \gamma_\mu P_{R(L)} b \right) \left( \bar{\ell} \gamma^\mu \gamma_5 \ell \right) \]

\[ \mathcal{O}_P^{()} \propto \left( \bar{s} P_{R(L)} b \right) \left( \bar{\ell} \gamma^\mu \gamma_5 \ell \right) \]

\[ b \rightarrow s \gamma \]

\[ b \rightarrow s \ell \ell \]

\[ B_{(s)}^0 \rightarrow \ell^+ \ell^- \]
This decay is described by 3 angles \((\theta_I, \theta_K, \phi)\) and the di-muon invariant mass squared \((q^2)\)

This is analogous to the orbitals in atoms, i.e. the spectroscopy allows you to infer about atomic potential

\[
\begin{align*}
B^0 & \rightarrow K^* (\rightarrow K^+ \pi^-) \mu^+ \mu^- \\
\frac{1}{\Gamma} \frac{d^3 (\Gamma + \Gamma')}{d \cos \theta_\ell \ d \cos \theta_K \ d \phi} &= \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \\
&- F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + \\
&\sqrt{F_L (1 - F_L)} P_5' \sin 2\theta_K \sin \theta_\ell \cos \phi + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + \\
&S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right] 
\end{align*}
\]
$B^0 \rightarrow K^* (\rightarrow K^+ \pi^-) \mu^+ \mu^-$
Measurement of $P_{5'}$

- Discrepancy first observed in 2013 with $1\text{fb}^{-1}$
- Confirmed consistent result in 2016 with $3\text{fb}^{-1}$
- Analysis with Run 2 dataset ongoing
ATLAS, CMS and Belle also measured this quantity.
The discrepancy in $P_{5}'$ wrt SM can be interpreted as NP in either $C_9$ or $C_{9/10}$ simultaneously.
A Coherent Pattern?

- Data consistently below SM predictions
- Large theory uncertainty due to form factors
• Both $P_5'$ and the branching ratios discrepancy can be explain with the same shift in $C_9$ or $C_{9/10}$
• Charm loop contribution is essentially a correction to $C_9$ not possible to compute this contribution reliably

• Long debate on the community if the relatively large effect we see is NP or can be attributed to charm loop
• Charm loop can be considered as the sum of the tails of all resonances + open charm
Way Forward

- It is difficult to disentangle short distance and long distance contributions
- A few attempts:
  - Parametrizing the charmonia resonance as BW (including tails away from resonances) *EPJC 78 (6) 453 (2018)*
Phase Difference with Charmonia

- Fit of the $q^2$ spectrum, parametrising the resonances as relativistic BW

\[
\frac{d\Gamma}{dq^2} = \frac{G_F^2 \alpha^2 |V_{tb}V_{ts}^*|^2}{128\pi^5} |k|/\beta \left\{ \frac{2}{3} |k|^2 \beta^2 |C_{10} f_+(q^2)|^2 + \frac{4m^2_{\mu}(m^2_B - m^2_K)}{q^2m^2_B} |C_{10} f_0(q^2)|^2 \right. \\
+ \left. |k|^2 \left[ 1 - \frac{1}{3} \beta^2 \right] |C_9 f_+(q^2) + 2C_7 \frac{m_B + m_s}{m_B + m_K} f_T(q^2)|^2 \right\}
\]

**Diagram:**
- Graph showing candidates per (5 MeV/c^2)
- LHCb data
- Comparison with Standard Model (SM)
LFU in Rare Decays

Electron emit bremsstrahlung photons spoiling $q^2$, invariant mass and momentum resolutions:
- More complicate and difficult J/$\psi$ veto
- Harder trigger, reconstruction, PID, smaller efficiency wrt muons

$$u, d \quad u, d$$
$$\bar{b} \quad \bar{s}$$
$$\mu^+$$
$$\mu^-$$

$$u, d \quad u, d$$
$$\bar{b} \quad \bar{s}$$
$$e^+$$
$$e^-$$

$$= 1.0 \pm 0.1$$

EPJC 76 (2016) 8, 440

Nico Serra - Pheno 2019 6th - 8th May 2019
Electron emit bremsstrahlung photons spoiling $q^2$, invariant mass and momentum resolutions:
- More complicate and difficult $J/\psi$ veto
- Harder trigger, reconstruction, PID, smaller efficiency wrt muons
- Critical aspect in these analyses is the double ratio with the corresponding $J/\psi$ modes

$$= 1.0 \pm 0.1$$
LFU in Rare Decays

\[
R(K^*) = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}e^+e^-)} \quad \frac{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))}
\]

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

\[\text{LHCb} \quad B^0 \to K^{*0}J/\psi \quad \text{Combinatorial} \quad \text{LHCb} \quad B^0 \to K^{*0}J/\psi \quad \text{Combinatorial} \]

JHEP 1708 (2017) 055
\[
R(K^*) = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)} \frac{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))}
\]

- Mass fit model taken from the fit to \( B^0 \to J/\psi K^* \)
- Specific bkg taken from MC after data/MC corrections
Discrepancy with respect to the SM, numerically consistent with the $b \rightarrow s \mu \mu$

Surprising result at low $q^2$, would expect this part to be dominated by the photon contribution, but large statistical error still

Compatibility with SM 2.2-2.4σ (low-$q^2$) 2.4-2.5σ (central-$q^2$)

Only 3 fb$^{-1}$ of Run1 (6 fb$^{-1}$ of Run2 available) used for this analysis
LFU in Rare Decays

Ratio of efficiency determined with simulation using control channels:
- B-momentum kinematics, Tracking Efficiency,
- Particle Identification
- Trigger calibration
- Calibration of $q^2$ distribution and invariant mass

$R(K^+) = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-) \mathcal{B}(B^+ \to K^+J/\psi(\to e^+e^-))}{\mathcal{B}(B^+ \to K^+e^+e^-) \mathcal{B}(B^+ \to K^+J/\psi(\to \mu^+\mu^-))}$
LFU in Rare Decays

\[ r_{J/\psi} = 1.014 \pm 0.035 \text{ (stat. + syst.)} \]

\[ R_{\psi(2S)} = \frac{B(B^+ \to K^+\psi(2S)(\mu^+\mu^-))}{B(B^+ \to K^+J/\psi(\mu^+\mu^-))} \frac{B(B^+ \to K^+\psi(2S)(e^+e^-))}{B(B^+ \to K^+J/\psi(e^+e^-))} = 0.986 \pm 0.013 \text{ (stat + syst)} \]
LFU in Rare Decays

\[ R(K^+) = \frac{\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \rightarrow K^+e^+e^-)} \cdot \frac{\mathcal{B}(B^+ \rightarrow K^+J/\psi(\rightarrow e^+e^-))}{\mathcal{B}(B^+ \rightarrow K^+J/\psi(\rightarrow \mu^+\mu^-))} = \frac{\int 6.0 GeV^2 \frac{d\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)}{dq^2}}{\int 1.1 GeV^2 \frac{d\mathcal{B}(B^+ \rightarrow K^+e^+e^-)}{dq^2}} \]

\[ = 0.846_{-0.054^{(stat)}}^{+0.060^{(stat)}}{_{-0.014^{(syst)}}^{+0.016^{(syst)}}} \]

- 1.9 sigmas compatibility between Run1 and Run2
- Combined dataset 2.5 sigmas from SM predictions

Run1 + 2fb\(^{-1}\) (out of 6fb\(^{-1}\)) of Run2 (2015/2016)

\[ R_{K \text{ Run 1}}^{\text{new}} = 0.717_{-0.071}^{+0.083} + 0.017_{-0.016}^{+0.017} \]
\[ R_{K \text{ Run 1}}^{\text{old}} = 0.745_{-0.074}^{+0.090} \pm 0.036 \]
\[ R_{K \text{ Run 2}} = 0.928_{-0.076}^{+0.089} + 0.020 \]

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LHCb-PAPER-2019-009

6th - 8th May 2019
\[ B_{s,d} \rightarrow \mu^+\mu^- \]

- Precise SM prediction
  C. Bobeth et al. PRL 112, 101801 (2014)

\[ BR(B_s \rightarrow \mu^+\mu^-)_{SM} = (3.65 \pm 0.23) \times 10^{-9} \quad BR(B^0 \rightarrow \mu^+\mu^-)_{SM} = (1.06 \pm 0.09) \times 10^{-10} \]

- First observation (7.8\(\sigma\)) by a single experiment experiment:
  PRL 118 (2017) 191801

\[ BR(B_s \rightarrow \mu^+\mu^-)_{LHCb} = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \quad BR(B^0 \rightarrow \mu^+\mu^-)_{LHCb} = (1.5^{+1.2+0.2}_{-1.0-0.1}) \times 10^{-10} \]

- \( B_{s,d} \rightarrow \mu^+\mu^- \) branching ratio sensitive to scalar and pseudo-scalar contributions, which lift helicity suppression

- No large enhancement, but still precise measurement of this decay sensitive to \( C_{10} \):

\[ BR(B_s \rightarrow \mu^+\mu^-) \propto |C_{10} - C'_{10}|^2 \]
Wilson Coefficient Fits

J Matias et al., Portoz 2019 & 1903.09578

Nico Serra - Pheno 2019

D. Straub Moriond EW 2019 & 1903.10434

23 6th - 8th May 2019
- The decay $B^0 \to K^* \mu^+ \mu^-$ allows also to probe $C_{10}$

![Diagram showing expectations from $B_s \to \mu \mu$ and $B^0 \to K^* \mu \mu$]

My own extrapolation from current experimental results and using arXiv:1805.06378

- $R(K^*)$ measurement with full Run1+Run2 (only Run1)
- $R(K)$ measurement with full Run1+Run2 (only Run1 + 2015-2016)
- Measurement of other related decays $R(\phi), R(K\pi\pi), R(\Lambda^{(*)})$
- Measurement of non-LFU angular asymmetries in $B^0 \to K^* \ell^+ \ell^-$ such as $\Delta P_5'$
- Measurement of $C_{9}^{\mu\mu} - C_{9}^{ee}$ and $C_{10}^{\mu\mu} - C_{10}^{ee}$  Phys. Rev. D 99, 013007 (2019)
<table>
<thead>
<tr>
<th></th>
<th>BaBar</th>
<th>Belle</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>#B's produced</td>
<td>$O(400M)$</td>
<td>$O(700M)$</td>
<td>$O(800B)^*$</td>
</tr>
<tr>
<td>Production mechanism</td>
<td>$\Upsilon(4S) \rightarrow BB$</td>
<td>$\Upsilon(4S) \rightarrow B\bar{B}$</td>
<td>$pp \rightarrow gg \rightarrow b\bar{b}$</td>
</tr>
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</table>
LFU with Semileptonic

\[
R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)}{\mathcal{B}(B \rightarrow D^{(*)}\mu\nu)} = \frac{\text{Signal}}{\text{Normalization}}
\]

- B-factories exploit the fact that $B_{\text{sig}}$ momentum
- B-factories use the electron, muon and hadronic modes
- LHCb only uses $\tau \rightarrow \mu 2\nu$ and $\tau \rightarrow 3\pi\nu$
- B-factories have cleaner events, while LHCb larger statistics

\[\tau \rightarrow \mu 2\nu \quad \text{and} \quad \tau \rightarrow 3\pi\nu\]
LFU with Semileptonic

\[(\gamma \beta \bar{z})_B \simeq (\gamma \beta \bar{z})_{D*\mu} \Rightarrow (p\bar{z})_B = \frac{m_B}{m(D*\mu)}(p\bar{z})_{D*\mu}\]

- Fit of $E^*$ and missing mass using template from the simulation tuned with data
- Background from $B \to D^* D_{(s)}$ and from $B \to D^{**} \ell\nu$ taken from control regions

LHCb simulation

Supplementary material PRL115(2015)111803
LFU with Semileptonic

$\tau \rightarrow \mu 2\nu$


$$R(D^*)_{\tau \rightarrow \mu 2\nu} = 0.336 \pm 0.027 \pm 0.030$$

SM Prediction

$$R(D^*)_{SM} = 0.252 \pm 0.003 \ (S.\ Fajfer\ et\ al.\ 2012)$$

$\tau \rightarrow 3\pi\nu$


$$R(D^*)_{\tau \rightarrow 3\pi\nu} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$$
Tension wrt SM predictions goes from 3.8σ (pre-Moriond 2019) to 3.1σ (post-Moriond 2019).

\[ \mathcal{R}(D^{*}) = 0.307 \pm 0.037 \pm 0.016 \]

\[ \mathcal{R}(D) = 0.283 \pm 0.018 \pm 0.014 \]
Near Future

- Measurement of R(D*) from LHCb still with Run1, but much better trigger efficiency for Run2

- Several measurements in the pipeline:
  - Simultaneous measurement of R(D*) and R(D^0) with Run1 + Run2
  - Measurement of R(D_s) with Run2
  - Measurement of R(D^+) and R(D*) with Run2
  - Measurement of R(Λ_c) with Run2

Less feed-down background
Belle II experiment at SuperKEK:

- Target Luminosity

\[ \mathcal{L} = 8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1} \Rightarrow 10^{10} \bar{B}B, \tau^+\tau^-, c\bar{c} \text{ pairs} \int \mathcal{L} dt > 50 \text{ab}^{-1} \]

Improvements wrt Belle:
- Capability to deal with higher bkg, radiation damage, occupancy
- Higher trigger efficiency
- Improved performances and hermeticity
First $B\bar{B}$ event seen in Belle II detector
Charged tracks reconstructed using info mostly from the CDC are available since the beginning of collisions.

Mass resolutions of known particles in data in agreement with simulations (B field measured well and sub-detectors also aligned)

Gagan Mohanty, Moriond EW 2019

- Physics run of Belle2 started:
  - First results envisaged for LP2019
  - Significant luminosity ~2022

Belle II Physics Book
arXiv:1808.10567
LHCb Upgrades

- Upgrade of the LHCb detector during LHC LS2 (2019-20):
  - Change subdetector electronics to 40 MHz readout
  - All trigger decision software
  - Start data taking in 2021
  - Upgrade detector qualified to accumulate 50fb⁻¹

In order to exploit the full potential of the LHC, it is natural to have a further major LHCb upgrade during LS4

The Upgrade II will allow to increase data sample from 50fb⁻¹ to 300fb⁻¹
LHCb Upgrades

Charm loop effect fixed

Physics of the HL-LHC, WG 4
Flavour [arxiv:1812.07638]

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\Delta C_9$</th>
<th>$\Delta C_{10}$</th>
</tr>
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<tbody>
<tr>
<td>SM</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>I</td>
<td>-1.4</td>
<td>0</td>
</tr>
<tr>
<td>II</td>
<td>-0.7</td>
<td>+0.7</td>
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<tr>
<td>III</td>
<td>+0.3</td>
<td>+0.3</td>
</tr>
<tr>
<td>IV</td>
<td>+0.3</td>
<td>-0.3</td>
</tr>
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LHCb Upgrades

Run 3

Upgrade II

Scenario | $\Delta C_9$ | $\Delta C_{10}$
---|---|---
SM | 0 | 0
I | -1.4 | 0
II | -0.7 | +0.7

[Upgrade II Physics case] [Physics of the HL-LHC WG 4]

<table>
<thead>
<tr>
<th>Yield</th>
<th>Run 1 result</th>
<th>9 fb$^{-1}$</th>
<th>23 fb$^{-1}$</th>
<th>300 fb$^{-1}$</th>
</tr>
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<tbody>
<tr>
<td>$B^+ \to K^+e^+e^-$</td>
<td>254 ± 29</td>
<td>1120</td>
<td>3300</td>
<td>46000</td>
</tr>
<tr>
<td>$B^0 \to K^0 e^+e^-$</td>
<td>111 ± 14</td>
<td>490</td>
<td>1400</td>
<td>20000</td>
</tr>
<tr>
<td>$B^0 \to \phi e^+e^-$</td>
<td>-</td>
<td>80</td>
<td>230</td>
<td>3300</td>
</tr>
<tr>
<td>$A^0 \to pKe^+e^-$</td>
<td>-</td>
<td>120</td>
<td>360</td>
<td>5000</td>
</tr>
<tr>
<td>$B^+ \to \pi^+ e^+e^-$</td>
<td>-</td>
<td>20</td>
<td>70</td>
<td>900</td>
</tr>
</tbody>
</table>

$R_X$ precision

| $R_K$ | 0.745 ± 0.090 ± 0.036 | 0.043 | 0.025 | 0.007 |
| $R_{K^0}$ | 0.69 ± 0.11 ± 0.05 | 0.052 | 0.031 | 0.008 |
| $R_{\phi}$ | - | 0.130 | 0.076 | 0.020 |
| $R_{pK}$ | - | 0.105 | 0.061 | 0.016 |
| $R_{\pi}$ | - | 0.302 | 0.176 | 0.047 |

[CERN-LHCC-2017-003]
[CERN-LHCC-2018-027]

Physics of the HL-LHC, WG 4
Flavour [arxiv:1812.07638]

Nico Serra - Pheno 2019
6th - 8th May 2019
LHCb Upgrades

Expected LHCb sensitivity with Upgrade II: \( \frac{\sigma(R(D^*))}{R(D^*)} \sim 1\% \)

Angular analysis of semi-tauonic decays allow to determine spin structure of potential NP contribution.
Belle II and LHCb Upgrades

- Time dependent $B_s$ physics
  - CPV in $B_s \rightarrow J/\psi \phi$, $B_s \rightarrow \phi \phi$
- $B_s \rightarrow \mu^+ \mu^-$
- CKM angle $\gamma$
- CPV in $B_d$
- $B \rightarrow X_s \ell^+ \ell^-$ (exclusive) $\rightarrow$ LFU
- $B \rightarrow X_s \gamma$ (exclusive)
- Charm physics
- Semileptonic B decays
- $B \rightarrow D \tau^- \nu$, $B \rightarrow D^* \tau^- \nu$
- Dark matter
- $\tau -$ physics: LFV

- $B \rightarrow \tau^- \nu$, $B \rightarrow \mu^- \nu$
- $B \rightarrow K^* \nu \nu$, $B \rightarrow \nu \nu$
- $B \rightarrow X_s \ell^+ \ell^-$ (inclusive)
- $B \rightarrow X_s \gamma$ (inclusive)

"$B_s$ & charged tracks"

Important overlap: sporty competition!

"inclusive & neutrals"

J. Albrecht Portoroz 2019
Conclusions

- Intriguing pattern of anomalies in rare and semi-leptonic decays, measured by LHCb, BaBar and Belle

- Still need much larger statistics to understand if these anomalies are a genuine sign of PBSM

- More results will come from LHCb Run2 analyses for both anomalies

- Belle II and LHCb Upgrades will allow to further clarify the situation and if these anomalies are due to NP to disentangle between different scenarios
Let’s hope this story doesn’t have a disappointing finale
Backup Slides
LHCb Experiment
- LHCb operates at a constant levelled optimal luminosity (lower wrt GPD)
- Best compromise between clean events and high luminosity
LHCb experiment

- Single arm forward spectrometer $2.0 < y < 5.0$
- Levelled luminosity $2 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$
- Good particle identification (e.g. $\pi \rightarrow \mu \sim 0.5\%$)
- Excellent momentum resolution ($\delta p/p \sim 0.5\%$)
LHCb Performances

- **IP x resolution [μm]**
  - Graph showing 2012 data and simulation.

- **Resonance Mass resolution (MeV/c²)**
  - $J/\psi$: 14.3 ± 0.1
  - $\psi(2S)$: 16.5 ± 0.4
  - $\Upsilon(1S)$: 42.8 ± 0.1
  - $\Upsilon(2S)$: 44.8 ± 0.1
  - $\Upsilon(3S)$: 48.8 ± 0.2
  - $Z^0$: 1727 ± 64

- **Candidates/(22 MeV/c²)**
  - Graph showing $M_{\mu\mu}$ [GeV/c²].

- **$\sigma_m$ [MeV/c²]**
  - Graph showing $m$ [MeV/c²] with a linear fit.
Amplitude $B \rightarrow K^*\text{mm}$
• The decay is described by six complex amplitudes $A_{0,||,\perp}^{L,R}$

• Correspond to different transversity state of the $K^*$

• and different (left- and right-handed) chiralities of the dimuon system

\[
F_L = \frac{A_0^2}{A_0^2 + A_1^2 + A_0^2} = 1 - F_T
\]
\[
S_3 = \frac{A_1^L - A_1^L}{2 A_0^2 + A_1^2 + A_0^2} + L \rightarrow R
\]
\[
S_4 = \frac{\Re(A_0^L A_1^L)}{\sqrt{2} A_0^2 + A_1^2 + A_0^2} + L \rightarrow R
\]
\[
S_5 = \frac{\sqrt{2} \Re(A_0^L A_1^L)}{A_0^2 + A_1^2 + A_0^2} - L \rightarrow R
\]
\[
A_{FB} = \frac{8 \Re(A_0^L A_1^L)}{3 A_0^2 + A_1^2 + A_0^2} - L \rightarrow R
\]
\[
S_7 = \sqrt{2} \frac{\Im(A_0^L A_1^L)}{A_0^2 + A_1^2 + A_0^2} + L \rightarrow R
\]
\[
S_8 = \frac{1}{\sqrt{2}} \frac{\Im(A_0^L A_1^L)}{A_0^2 + A_1^2 + A_0^2} + L \rightarrow R
\]
\[
S_9 = \frac{\Im(A_0^L A_1^L)}{A_0^2 + A_1^2 + A_0^2} - L \rightarrow R
\]

\[
A_{0,||,\perp}^{L,R} \propto \left[ C_{9\mp10}^+ A_{12} + C_{7}^+ T_{23} \right]
\]
\[
R_1 = \frac{T_1}{V} \sim 1
\]
\[
R_2 = \frac{T_2}{A_{12}} \sim 1
\]
\[
R_3 = \frac{T_{23}}{A_{12}} \sim \frac{q^2}{m_B^2}
\]

\[
A_{\perp}^{L,R} = \sqrt{2} N m_B (1 - \hat{s}) \left[ (C_9^{\text{eff}} - C_9'^{\text{eff}}) \mp (C_{10} - C_{10}') + \frac{2 \hat{m}_b}{\hat{s}} (C_7^{\text{eff}} - C_7'^{\text{eff}}) \right] \xi_{\perp}(E_{K^*})
\]

\[
A_{||}^{L,R} = -\sqrt{2} N m_B (1 - \hat{s}) \left[ (C_9^{\text{eff}} - C_9'^{\text{eff}}) \mp (C_{10} - C_{10}') + \frac{2 \hat{m}_b}{\hat{s}} (C_7^{\text{eff}} - C_7'^{\text{eff}}) \right] \xi_{||}(E_{K^*})
\]

\[
A_0^{L,R} = -\frac{N m_B (1 - \hat{s})^2}{2 \hat{m}_K \sqrt{\hat{s}}} \left[ (C_9^{\text{eff}} - C_9'^{\text{eff}}) \mp (C_{10} - C_{10}') + 2 \hat{m}_b (C_7^{\text{eff}} - C_7'^{\text{eff}}) \right] \xi_{||}(E_{K^*})
\]
We now build ratios such that the same combination of FF appears in the numerator and in the denominator.

\[
\begin{align*}
A_{0}^{L,R} & \propto \left[ C_{9 \mp 10}^{+} A_{12} + C_{7}^{+} T_{23} \right] \\
A_{\parallel}^{L,R} & \propto \left[ C_{9 \mp 10}^{-} A_{1} + C_{7}^{-} T_{2} \right] \\
A_{\perp}^{L,R} & \propto \left[ C_{9 \mp 10}^{-} V + C_{7}^{-} T_{1} \right]
\end{align*}
\]

\[
R_{1} = \frac{T_{1}}{V} \sim 1
\]

\[
R_{2} = \frac{T_{2}}{A_{1}} \sim 1
\]

\[
R_{3} = \frac{T_{23}}{A_{12}} \sim \frac{q^{2}}{m_{B}^{2}}
\]

\[
\begin{align*}
A_{\perp}^{L,R} & = \sqrt{2N m_{B}} (1 - \hat{s}) \left[ (C_{9}^{\text{eff}} + C_{9}^{\text{eff}'} \mp (C_{10} + C_{10}') + \frac{2\hat{m}_{b}}{\hat{s}} (C_{7}^{\text{eff}} + C_{7}^{\text{eff}'} \right] \xi_{\perp}(E_{K^{\ast}}) \\
A_{\parallel}^{L,R} & = -\sqrt{2N m_{B}} (1 - \hat{s}) \left[ (C_{9}^{\text{eff}} - C_{9}^{\text{eff}'} \mp (C_{10} - C_{10}') + \frac{2\hat{m}_{b}}{\hat{s}} (C_{7}^{\text{eff}} - C_{7}^{\text{eff}'} \right] \xi_{\parallel}(E_{K^{\ast}}) \\
A_{0}^{L,R} & = -\frac{N m_{B} (1 - \hat{s})^{2}}{2\hat{m}_{K^{\ast}} \sqrt{\hat{s}}} \left[ (C_{9}^{\text{eff}} - C_{9}^{\text{eff}'} \mp (C_{10} - C_{10}') + 2\hat{m}_{b} (C_{7}^{\text{eff}} - C_{7}^{\text{eff}'} \right] \xi_{\parallel}(E_{K^{\ast}})
\end{align*}
\]

\[
P_{5}^{'} \propto \frac{\Re(A_{0} A_{\perp})}{\sqrt{|A_{0}|^{2} \times |A_{\perp}|^{2}}}
\]
- The number of degrees of freedom are $3 \times 2 \times 2 = 12$
- However there are 4 symmetries of the angular distributions, so there are 8 independent observables
- The maximum number of “clean” observables is 6

\[
P_1 = A_T^{(2)} = \frac{2S_3}{(1 - F_L)} = \frac{A_L^2 - A_L^L}{A_L^2 + A_L^L} + L \rightarrow R
\]
\[
P_2 = 2A_T^{Re} = \frac{2A_{FB}}{3(1 - F_L)} \propto \frac{\Re(A_L^L A_L^L)}{A_L^2 + A_L^L} - L \rightarrow R
\]
\[
P_3 = S_0 \frac{1}{1 - F_L} = \frac{\Im(A_L^L A_L^L)}{A_L^2 + A_L^L} - L \rightarrow R
\]
\[
P_4' = \frac{S_4}{\sqrt{F_L(1 - F_L)}} \propto \frac{\Re(A_0^L A_L^L)}{\sqrt{|A_0|^2 |A_L|^2}} + L \rightarrow R
\]
\[
P_5' = \frac{S_5}{\sqrt{F_L(1 - F_L)}} \propto \frac{\Re(A_0^L A_L^L)}{\sqrt{|A_L|^2 |A_0|^2}} - L \rightarrow R
\]
\[
P_6' = \frac{S_7}{\sqrt{F_L(1 - F_L)}} \propto \frac{\Im(A_0^L A_L^L)}{\sqrt{|A_L|^2 |A_0|^2}} + L \rightarrow R
\]
Analysis B $\rightarrow$ K*mm
Selection

- JHEP 1602 (2016) 104
- PID, kinematics and isolation variables used in a Boosted Decision Tree (BDT) to reject background.
- Reject the regions of $J/\psi$ and $\psi(2S)$.
- Specific vetos for backgrounds: $\Lambda_b \rightarrow pK\mu\mu$, $B^0_s \rightarrow \phi\mu\mu$, etc.
- Using k-Fold technique and signal proxy $B \rightarrow J/\psi K^*$ for training the BDT.
- Improved selection allowed for finer binning than the $1\text{fb}^{-1}$ analysis.
Acceptance

- Detector distorts our angular distribution.
- We need to model this effect.
- 4D function is used:

\[ \epsilon(\cos \theta_i, \cos \theta_k, \phi, q^2) = \sum_{ijkl} P_i(\cos \theta_i) P_j(\cos \theta_k) P_k(\phi) P_l(q^2), \]

where \( P_i \) is the Legendre polynomial of order \( i \).
- We use up to \( 4^{th}, 5^{th}, 6^{th}, 5^{th} \) order for the \( \cos \theta_i, \cos \theta_k, \phi, q^2 \).
- The coefficients were determined using Method of Moments, with a huge simulation sample.
- The simulation was done assuming a flat phase space and reweighing the \( q^2 \) distribution to make is flat.
Methods

1. Maximum likelihood fit:
   - The most standard way of obtaining the parameters.
   - Can have problem with low statistics.

2. Method of moments:
   - Less precise than the likelihood estimator (10 – 15% larger uncertainties).
   - Does not suffer from the problems of likelihood fit.

3. Amplitude fit:
   - Incorporates all the physical symmetries inside the amplitudes! The most precise estimator.
   - Has theoretical assumptions inside!
$B^0 \rightarrow K^*0 \mu^+ \mu^-$

- Four dimensional fit of B-mass, angles ($\phi, \theta_\ell, \theta_K$) and simultaneous fit of $m(K\pi)$ (background fraction shared)

$$
\log \mathcal{L} = \sum_i \log \left[ \epsilon(\Omega, q^2) f_{\text{sig}} \mathcal{P}_{\text{sig}}(\Omega) \mathcal{P}_{\text{sig}}(m_{K\pi\mu\mu}) + (1 - f_{\text{sig}}) \mathcal{P}_{\text{bkg}}(\Omega) \mathcal{P}_{\text{bkg}}(m_{K\pi\mu\mu}) \right] + \\
\sum_i \log \left[ f_{\text{sig}} \mathcal{P}_{\text{sig}}(m_{K\pi}) + (1 - f_{\text{sig}}) \mathcal{P}_{\text{bkg}}(m_{K\pi}) \right]
$$

- $\mathcal{P}_{\text{sig}}(\Omega) = \frac{d^3 \Gamma}{d \cos \theta_\ell d \cos \theta_K d \phi}$ and $\epsilon(\Omega, q^2)$ is the signal efficiency

- $\mathcal{P}_{\text{bkg}}(\Omega)$ is modelled with three second order Chebychel polynomial and extracted from the sidebands

- $\mathcal{P}_{\text{bkg}}(m_{K\pi\mu\mu})$ is an exponential
In the maximum likelihood fit one could weight the events accordingly to the 
\[ \frac{1}{\varepsilon(\cos \theta_i, \cos \theta_k, \phi, q^2)} \]
Better alternative is to put the efficiency into the maximum likelihood fit itself:

\[ L = \prod_{i=1}^{N} \varepsilon_i(\Omega_i, q_i^2) \mathcal{P}(\Omega_i, q_i^2) / \int \varepsilon(\Omega, q^2) \mathcal{P}(\Omega, q^2) d\Omega dq^2 \]

Only the relative weights matters!
The Procedure was commissioned with TOY MC study.
Use Feldmann-Cousins to determine the uncertainties.
Angular background component is modelled with 2\textsuperscript{nd} order Chebyshev polynomials, which was tested on the side-bands.
S-wave component treated as nuisance parameter.
Method of Moments

Use orthogonality of spherical harmonics to determine the coefficients

$$\int f_i(\Omega) f_j(\Omega) d\Omega = \delta_{ij}$$

$$M_i = \int \left( \frac{1}{d(\Gamma + \vec{\Gamma})/dq^2} \right) \frac{d^3(\Gamma + \vec{\Gamma})}{d\Omega} f_i(\Omega) d\Omega$$

We sample the angular distribution with our data, so the integral becomes a sum over data

$$\hat{M}_i = \frac{1}{\sum_e w_e} \sum_e w_e f_i(\Omega_e)$$

The weights $w_e$ accounts for the efficiency
Amplitude Fit

⇒ Fit for amplitudes as (continuous) functions of $q^2$ in the region: $q^2 \in [1.1.6.0] \text{ GeV}^2/c^4$.
⇒ Needs some Ansatz:

$$A(q^2) = \alpha + \beta q^2 + \frac{\gamma}{q^2}$$

⇒ The assumption is tested extensively with toys.
⇒ Set of 3 complex parameters $\alpha, \beta, \gamma$ per vector amplitude:
  • $L, R, 0, \|, \perp, i, \otimes \rightarrow 3 \times 2 \times 3 \times 2 = 36 \text{ DoF}$.
  • Scalar amplitudes: +4 DoF.
  • Symmetries of the amplitudes reduces the total budget to: 28.
⇒ The technique is described in JHEP06(2015)084, U. Egede, M. Patel, K.A. Petridis.
⇒ Allows to build the observables as continuous functions of $q^2$:
  • At current point the method is limited by statistics.
  • In the future the power of this method will increase.
⇒ Allows to measure the zero-crossing points for free and with smaller errors than previous methods.
- Total signal yield integrated in $q^2$: $2398 \pm 58$ events
- Angular analysis performed in small $q^2$ bins is more sensitive to NP contributions
- High significance of the signal in all bins
- Independent angular and mass fits in each bins
- Very good agreement with the expected angular distributions in the control channel
Results
Results
Zero crossing points:

\[ q_0(S_4) < 2.65 \quad \text{at 95% CL} \]
\[ q_0(S_5) \in [2.49, 3.95] \quad \text{at 68% CL} \]
\[ q_0(A_{FB}) \in [3.40, 4.87] \quad \text{at 68% CL} \]
Use EOS software package to test compatibility with SM.
Perform the $\chi^2$ fit to the measured:

$$ F_L, A_{FB}, S_3, \ldots, 9. $$

Float a vector coupling: $R(C_9)$.
Best fit is found to be $3.4 \, \sigma$ away from the SM.
Interpretation $B \rightarrow K/K^\ast \text{mm}$
- Missing newest data from $R_K$, not as coherent as before
- However, more effects have to be considered, including NFC from $b \rightarrow s\tau\tau$
High $q^2$ region

- LHCb has evidence of resonance structures in the high $q^2$ region of $B^+ \to K^+ \mu^+ \mu^-$
- First observation of $B^+ \to K^+\psi(4160)(\to \mu^+\mu^-)$

Extrapolation from BESII assuming QCD factorisation

Lyons and Zwicky arXiv:1406.0566

Resonance structure at high $q^2$ failure of factorisation
A New Particle?

- Different contributions from charm loop (parameterized as the interference with the J/ψ) can change the behaviour of $P_{5'}$

- New Physics must be a flat contribution in the Wilson coefficient(s) as a function of $q^2$

- Up to now consistent with flat, but more statistics needed

- We are developing a method to determine the non-flat hadronic contribution directly from data!
Unbinned $B \rightarrow K^* \pi \pi$
Charm Loop

\[
\frac{d\Gamma}{dq^2} = \frac{G_F^2 \alpha^2 |V_{tb} V_{ts}^*|^2}{27 \pi^5} |k| \beta_+ \left\{ \frac{2}{3} |k| |k| \beta_+^2 \left| C_{10}^{\text{eff}} f_+(q^2) \right|^2 + \frac{m_t^2 (M_B^2 - M_K^2)^2}{q^2 M_B^2} \left| C_{10}^{\text{eff}} f_0(q^2) \right|^2 \right. \\
+ \left. |k|^2 \left[ 1 - \frac{1}{3} \beta_+^2 \right] \left| C_9^{\text{eff}} f_+(q^2) + 2 C_7^{\text{eff}} \frac{m_b + m_s}{M_B + M_K} f_T(q^2) \right|^2 \right\} ,
\]

(2.10)

Add resonances here.

We do not include any Y(q^2) term in C_9^{\text{eff}}.
Charm Loop

- Sensitive to $|C_9|^2 + |C_{10}|^2$.
- Can break degeneracy using e.g. $\text{BF}(B_s \rightarrow \mu \mu)$.

\[
\frac{d\Gamma}{dq^2} = \frac{G_F^2 \alpha^2 |V_{tb} V_{ts}^*|^2}{27\pi^5} |\mathbf{k}| \beta_+ \left\{ \frac{2}{3} |\mathbf{k}|^2 \beta_+^2 |C_{10}^{\text{eff}} f_+(q^2)|^2 + \frac{m_l^2 (M_B^2 - M_K^2)}{q^2 M_B^2} |C_{10}^{\text{eff}} f_0(q^2)|^2 \right. \\
+ |\mathbf{k}|^2 \left[ 1 - \frac{1}{3} \beta_+^2 \right] |C_9^{\text{eff}} f_+(q^2) + 2C_7^{\text{eff}} \frac{m_b + m_s}{M_B + M_K} f_T(q^2)|^2 \right\}
\]

Equation from Fermilab Lattice and MILC, Phys. Rev. D 93, 025026
Charm Loop

- Use latest Fermilab/MILC form factor calculations:

\[ f_+ / f_0 \]

\[ f_T \]

\[ q^2 (\text{GeV}^2) \]

Fermilab Lattice and MILC, Phys. Rev. D 93, 025026

- z-expansion coefficients allowed to float within uncertainties.
Charm Loop

- Results show minimal interference with $J/\psi$ and $\psi(2S)$ resonances.
  
  → Given this model, the $J/\psi$ and $\psi(2S)$ resonances play sub-dominant role below their pole mass.

- Phases of $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ in good agreement with Lyon Zwicky [1406.0566]

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$J/\psi$ negative/$\psi(2S)$ negative</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phase [rad]</td>
</tr>
<tr>
<td>$\rho(770)$</td>
<td>$-0.35 \pm 0.54$</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>$0.26 \pm 0.39$</td>
</tr>
<tr>
<td>$\phi(1020)$</td>
<td>$0.47 \pm 0.39$</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>$-1.66 \pm 0.05$</td>
</tr>
<tr>
<td>$\psi(2S)$</td>
<td>$-1.93 \pm 0.10$</td>
</tr>
<tr>
<td>$\psi(3770)$</td>
<td>$-2.13 \pm 0.42$</td>
</tr>
<tr>
<td>$\psi(4040)$</td>
<td>$-2.52 \pm 0.66$</td>
</tr>
<tr>
<td>$\psi(4160)$</td>
<td>$-1.90 \pm 0.64$</td>
</tr>
<tr>
<td>$\psi(4415)$</td>
<td>$-2.52 \pm 0.36$</td>
</tr>
</tbody>
</table>

- Constrains on $C_9$ and $C_{10}$ in agreement with other global analyses.

- Interference with resonances exclude $C_9 = 0$ at more than 5σ!

- Significantly improve precision on $b_1^+$ and $b_2^+$.
<table>
<thead>
<tr>
<th>Decay</th>
<th>% of $B^+ \to K^+ \mu^+ \mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penguin</td>
<td>0.6 %</td>
</tr>
<tr>
<td>$B^+ \to \rho K^+$</td>
<td>0.0003 %</td>
</tr>
<tr>
<td>$B^+ \to \omega K^+$</td>
<td>0.0006 %</td>
</tr>
<tr>
<td>$B^+ \to \phi K^+$</td>
<td>0.003 %</td>
</tr>
<tr>
<td>$B^+ \to J/\psi K^+$</td>
<td>92 %</td>
</tr>
<tr>
<td>$B^+ \to \psi(2S)K^+$</td>
<td>7.3 %</td>
</tr>
<tr>
<td>$B^+ \to \psi(3770)K^+$</td>
<td>0.007 %</td>
</tr>
<tr>
<td>$B^+ \to \psi(4040)K^+$</td>
<td>$\sim 0$ %</td>
</tr>
<tr>
<td>$B^+ \to \psi(4160)K^+$</td>
<td>0.005 %</td>
</tr>
<tr>
<td>$B^+ \to \psi(4415)K^+$</td>
<td>$\sim 0$ %</td>
</tr>
</tbody>
</table>

\[
\frac{d\Gamma}{dq^2} = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{2^7\pi^5} |k|\beta_+ \left\{ \frac{2}{3} |k|^2 \beta_+^2 |C_{10}^{\text{eff}} f_+(q^2)|^2 + \frac{m_i^2(M_B^2 - M_K^2)^2}{q^2M_B^2} |C_{10}^{\text{eff}} f_0(q^2)|^2 \right\}
\]
\[+ |k|^2 \left[ 1 - \frac{1}{3} \beta_+^2 \right] \left| C_9^{\text{eff}} f_+(q^2) + 2C_7^{\text{eff}} \frac{m_b + m_s}{M_B + M_K} f_T(q^2) \right|^2 \]
Charm Loop

\[ A^{L,R}_\lambda = N_\lambda \left\{ (C_9 + C_{10}) F_\lambda(q^2) + \frac{2m_b M_B}{q^2} \left[ C_7 F^T_\lambda(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\} \]

- Wilson coefficients
- Form factors
- Non-local hadronic matrix elements

Mapping \( q^2 \rightarrow z(q^2) \)

\[ \mathcal{H}_\lambda(z) = \frac{1 - zz^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - zz^*_{\psi(2S)}}{z - z_{\psi(2S)}} \hat{\mathcal{H}}_\lambda(z) \]

Polynomial expansion

\[ \hat{\mathcal{H}}_\lambda(z) = \left[ \sum_k \alpha_k^{(\lambda)} z^k \right] F_\lambda(z) \]

- analytic within \(|z| = 1\)
- expansion used up to \(z \sim 0.4\)
- cut-off of the series introduce a model bias
Extension of the parametrisation of the model in arXiv:1709.03921, including points at negative $q^2$

- Fit much more stable with the theory points, but not yet a rigorous procedure to evaluate systematics
LHCb Experiment

- Studying the order of the polynomial allows to inspect charm-loop effects.

- Uncertainty (slightly) increases with the order of the polynomial.

- Modeling of the charm-loop → main systematic

- Statistical uncertainty on the Wilson coefficients saturates already after Run II due to form factor uncertainties.

arXiv:1805.06378
**classic angular analysis**

2 steps procedure:
- fit for angular observables $S_i$
- fit for Wilson coeff. (using same model for charm-loop)

**VS**

**amplitude fit**

direct determination of Wilson coeff.

(include branching ratio information via an extended ML fit to signal yield)
RK*
**R_{K^*} Analysis**

- Fit MC in different trigger and bremsstrahlung categories to extract initial parameters (separately for all modes)

- Combine bremsstrahlung PDFs into one signal model per each trigger category (bremsstrahlung fractions fixed from MC)

- Fit the data in trigger categories allowing (some) parameters to vary

**Signal**
- $0\gamma$ (1$\gamma$ and 2$\gamma$)
- Free parameters
- Crystal-Ball (Crystal-Ball and Gaussian)
- mass shift and width scale

**Backgrounds**
- Combinatorial
- $\Lambda_b$
- $B_s$
- Leakage
- Part-Reco
- exponential
- simulation & data, yield constrained using muons
- same as signal but shifted by $m_{B_s} - m_{B_d}$, yield constrained using muons
- simulation, yield constrained using data
- simulation & data
R_{K^*} Analysis

Yield

<table>
<thead>
<tr>
<th></th>
<th>( B^0 \rightarrow K^{*0} \ell^+ \ell^- )</th>
<th>( B^0 \rightarrow K^{*0} J/\psi (\rightarrow \ell^+ \ell^-) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu^+ \mu^- )</td>
<td>low-( q^2 )</td>
<td>285 \pm 18</td>
</tr>
<tr>
<td></td>
<td>central-( q^2 )</td>
<td>274416 \pm 804</td>
</tr>
<tr>
<td>( e^+ e^- )</td>
<td>low-( q^2 )</td>
<td>55 \pm 9</td>
</tr>
<tr>
<td></td>
<td>central-( q^2 )</td>
<td>43468 \pm 222</td>
</tr>
<tr>
<td>( e^+ e^- )</td>
<td>low-( q^2 )</td>
<td>13 \pm 3</td>
</tr>
<tr>
<td></td>
<td>central-( q^2 )</td>
<td>3388 \pm 61</td>
</tr>
<tr>
<td>( e^+ e^- )</td>
<td>low-( q^2 )</td>
<td>21 \pm 4</td>
</tr>
<tr>
<td></td>
<td>central-( q^2 )</td>
<td>11505 \pm 115</td>
</tr>
</tbody>
</table>

Systematics

<table>
<thead>
<tr>
<th>( \Delta R_{K^{*0}} / R_{K^{*0}} ) [%]</th>
<th>low-( q^2 )</th>
<th>central-( q^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger category</td>
<td>L0E</td>
<td>L0H</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>
</tr>
<tr>
<td>PID</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Kinematic selection</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Residual background</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mass fits</td>
<td>1.4</td>
<td>2.1</td>
</tr>
<tr>
<td>Bin migration</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>( r_{J/\psi} ) ratio</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>
$R_{K^*}$ High $q^2$

- Very little rate for $q^2 < 1.0$ GeV$^2$ (no photon pole)

- Working to add high $q^2$ bin – difficulty same for $R_K$ and $R_{K^*}$
  - Rare decays with higher $K^*$ resonances can leak into signal region from below
  - $\psi(2S)K^*$ decays can leak into signal region on the upper side
  - Signal sandwiched between these and hence difficult to fit reliably
RK
\[ \text{LHCb simulation} \]

\[ \text{Candidates / (a. u.)} \]

\[ \alpha(l^+, l^-) \text{ [rad]} \]

\[ \text{Candidates / (a. u.)} \]

\[ \alpha(K^+, l^-) \text{ [rad]} \]

\[ \text{Candidates / (a. u.)} \]

\[ \alpha(K^+, l^-) \text{ [rad]} \]

\[ \text{Candidates / (a. u.)} \]

\[ \eta(K^+) \]

\[ \text{Candidates / (a. u.)} \]

\[ \max(\eta(l^+), \eta(l^-)) \]

\[ \cdots \quad B^+ \rightarrow K^+ e^+ e^- \]

\[ \cdots \quad B^+ \rightarrow K^+ \mu^+ \mu^- \]

\[ \cdots \quad B^+ \rightarrow J/ \psi (e^+ e^-) K^+ \]

\[ \cdots \quad B^+ \rightarrow J/ \psi (\mu^+ \mu^-) K^+ \]
LHCb simulation

Candidates / (a. u.)

$\max(p_T(l^+), p_T(l^-))$ [MeV/c]

$\min(p_T(l^+), p_T(l^-))$ [MeV/c]

$\log_{10}(\chi^2_{IP}(B^+))$

$\log_{10}(\chi^2_{Vtx}(B^+))$

$B^+ \rightarrow K^+ e^+ e^-$

$B^+ \rightarrow K^+ \mu^+ \mu^-$

$B^+ \rightarrow J/\psi(e^+ e^-)K^+$

$B^+ \rightarrow J/\psi(\mu^+ \mu^-)K^+$
Supplementary $r_{J/\psi b}$ 1D

![Graphs showing LHCb simulation results for $B^+ \rightarrow K^+ e^+ e^-$, $B^+ \rightarrow K^+ \mu^+ \mu^-$, $B^+ \rightarrow J/\psi(e^+ e^-)K^+$, and $B^+ \rightarrow J/\psi(\mu^+ \mu^-)K^+$ transitions.](image_url)

![Plots showing the ratio $r_{J/\psi b}$ as a function of dilepton opening angle and $p_T(B^+)$ in MeV/c.](image_url)
Cascade Vetos in RK

LHCb simulation

$$B^+ \rightarrow K^+ e^+ e^-$$

$$B^+ \rightarrow \bar{D}^0 \rightarrow K^+ e^- \nu$$

$$B^+ \rightarrow \bar{D}^0 \rightarrow K^+ e^- \pi^- \rightarrow e^-$$

$$B^+ \rightarrow \bar{D}^0 \rightarrow K^+ e^- \pi^- \rightarrow e^+ \nu$$

Normalized distribution

$$m(K^+ e^-) \text{ [MeV/c}^2\text{]}$$

Normalized distribution

$$m^{\text{track}}(K^+ e^- \rightarrow \pi^-) \text{ [MeV/c}^2\text{]}$$
RK Part Reco

LHCb simulation

Candidates / (a. u.)

$m(K^+ e^+ e^-)$ [MeV/$c^2$]

- $B \rightarrow K^* e^+ e^-$
- $B^+ \rightarrow K^+_1 e^+ e^-$
- $B^+ \rightarrow K^+_2 e^+ e^-$
- $B^+ \rightarrow K^+ J/\psi (\rightarrow e^+ e^-)$
- $B \rightarrow H_c (\rightarrow J/\psi X) K^+$
- or $B \rightarrow J/\psi H_b (\rightarrow K^+ Y)$
Bs $\rightarrow$ mm
Bs$\rightarrow$mm will stay statistically dominated till LHCb Upgrade II

<table>
<thead>
<tr>
<th>Source</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronisation fraction $f_s/f_d$</td>
<td>5.8%</td>
</tr>
<tr>
<td>Normalisation modes</td>
<td>3%</td>
</tr>
<tr>
<td>Particle identification</td>
<td>2%</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>2%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>now</th>
<th>23 fb$^{-1}$</th>
<th>300 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>absolute uncertainty $B_s^0 \rightarrow \mu^+\mu^-$ $[10^{-9}]$</td>
<td>0.67</td>
<td>0.30</td>
<td>0.16</td>
</tr>
<tr>
<td>rel. uncertainty $B^0 \rightarrow \mu^+\mu^-/B_s^0 \rightarrow \mu^+\mu^-$ [%]</td>
<td>90%</td>
<td>34%</td>
<td>10%</td>
</tr>
</tbody>
</table>
Semileptonic LHCb
Semileptonic

- B-factories measure tau->e,mu 2v
- LHCb measures tau->mu 2v

Since the D-meson is a scalar $H_+,-$ vanish
- Amplitudes depend on 4 universal FFs extracted from data
- Four free parameters in the fit
- In the case of the e/mu $H_S$ is suppressed by the mass, so this is only present in the channel with the tau (from HQET)
- Hadronic tag analyses:
  - Reconstruct tag B meson in all hadronic mode
  - Precise knowledge of kinematic of missing system
  - Kill background, but efficiency about $10^{-3}$

- Semileptonic analyses:
  - Tag B-meson in semileptonic channel
  - Selection: $E_T$, missing mass and angle between $D^*\ell$ and B

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu)} = \int_{m_\tau^2}^{q_{\max}^2} \frac{d\Gamma_{\tau}}{dq^2} \, dq^2$$
Semileptonic

- **$B \rightarrow D^* \tau \nu$**
- **$B \rightarrow D^* \mu \nu$**

- **Difficulty:** neutrinos - 2 for $(\tau \rightarrow \pi \pi \pi \nu) \nu$, 3 for $(\tau \rightarrow \mu \nu \nu) \nu$
  - No narrow peak to fit (in any distribution)
- **Main backgrounds:** partially reconstructed B decays
  - $B \rightarrow D^* \mu \nu, B \rightarrow D^{**} \mu \nu, B \rightarrow D^* D(\rightarrow \mu X) X \ldots$
  - $B \rightarrow D^* \pi \pi \pi X, B \rightarrow D^* D(\rightarrow \pi \pi \pi X) X \ldots$
- **Also combinatorial, misidentified background**
Semileptonic

- B-direction given by PV-SV
- Full fit of the MM, E*, q^2
- Muon, tau modes and bkg fit simultaneously

\[(\gamma \beta_z)_B = (\gamma \beta_z)_{D^*\mu} \quad \Rightarrow \quad (p_z)_B = \frac{m_B}{m(D^*\mu)} (p_z)_{D^*\mu}\]
- Large contribution from excited D** states
- Narrow states (D_1(′) and D_2*) fit directly from data B->D*ππ lv used as a control sample
- Higher D** excited states also fit from data and B->D ππ lv used as a control channel
Semileptonic

- As usual charm is a background for tau
- Bkg from $D_s \rightarrow \tau \nu$, $D \rightarrow K \nu \nu$ fit directly from data
- Control sample obtained reconstructing $B \rightarrow D^* K \nu \nu$
Semileptonic

- Fit to the control sample “D*π l”

- Fit to the control sample “D*ππ l”
- Fit to the control sample “D*K I”

- Similar simulated sample for B->DD_s with D_s->tau v
Systematics uncertainty for $R(D^*)$ in LHCb

<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>$B^0 \rightarrow D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors</td>
<td>0.6</td>
</tr>
<tr>
<td>$B \rightarrow D^{**}H_c(\rightarrow \mu\nu X')X$ 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>$B \rightarrow D^{**}(\rightarrow D^*\pi\pi)\mu\nu$ shape corrections</td>
<td>0.4</td>
</tr>
<tr>
<td>Corrections to simulation</td>
<td></td>
</tr>
<tr>
<td>Combinatorial background shape</td>
<td></td>
</tr>
<tr>
<td>$B \rightarrow D^{**}(\rightarrow D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors</td>
<td>0.3</td>
</tr>
<tr>
<td>$B \rightarrow D^{*+}(D_s \rightarrow \tau\nu)X$ fraction</td>
<td>0.1</td>
</tr>
<tr>
<td>Total model uncertainty</td>
<td>2.8</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>
<td>0.6</td>
</tr>
<tr>
<td>Hardware trigger efficiency</td>
<td>0.6</td>
</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>Total normalization uncertainty</td>
<td>0.9</td>
</tr>
</tbody>
</table>

| Total systematic uncertainty | 3.0                             |
• Ratios of branching fractions are only the first observable
  • $q^2$, angles, $\tau/D^*$ polarisation have different sensitivity to new physics
• Variables fitted in $\tau \rightarrow \mu \nu \nu$ analyses already have some sensitivity to this
  • For now, measurements assume SM distributions (+ uncertainties)
Semileptonic

- Angular resolution for $B \rightarrow D^* \mu \nu$ (black) and $B \rightarrow D^* \tau \nu$ (red)
- Tau decay results in degradation of resolution
- Pretty wide, but have something to work with
  - Interesting measurements also possible in muonic modes
- Ideas for how to exploit this, some tools already exist
- Sensitivity not yet known, may need larger samples to really pin things down.
Semileptonic

Semitauonic signal-side decay and semileptonic tag-side.

**Numerator in \( \mathcal{R}(D^*) \)**

**Denominator in \( \mathcal{R}(D^*) \)**

\[ D^* \text{ reconstruction:} \]

- \( D^{*-} \rightarrow D^0\pi^+, D^+\pi^0 \) \( \sim 100\% \)
- \( D^0 \): 10 modes \( \sim 37\% \)
- \( D^+ \): 5 modes \( \sim 22\% \)

**Tag semileptonic B-decay:** Combine \( D^{*-} \) and oppositely-charged lepton candidates and calculate the cosine of the angle between the \( B \) momentum and the \( D^*l \) in the \( \Upsilon(4S) \) frame.

\[ \text{Image credits: Y. Sato (Nagoya)} \]
Semileptonic tag using full event information
- Statistically independent from previous analyses based on hadronic tags
- Yields determined from 2D fit to extra calorimeter energy and BDT classifier
Semileptonic

$R(D^*)$ with $\tau \rightarrow \pi\pi\pi\nu$

- Measurement of $B(B \rightarrow D^*\tau\nu)$ also near completion using $\tau \rightarrow \pi\pi\pi\nu$
- Different sets of backgrounds:
  - Large $B \rightarrow D^*\mu\nu$, $B \rightarrow D^{**}\mu^+\nu$ backgrounds absent
  - Additional $B \rightarrow D^*\pi\pi\pi X$ backgrounds
  - $B \rightarrow D^*DX$ with $D \rightarrow \pi\pi\pi X$
- Control experimental efficiencies by measuring rate relative to $B \rightarrow D^*\pi\pi\pi$
  - Recent measurement from Babar for this purpose $\rightarrow 4.4\%$ uncertainty
Semileptonic

- Can use decay topology to remove direct $B \to D^{*} \pi \pi \pi X$ decays:
- If the $\pi \pi \pi$ vertex is displaced from the $B$ vertex, cannot be direct $B \to D^{*} \pi \pi \pi X$
- Can remove a large, poorly measured background
  - And control the remainder
- $B \to D^{*} DX$ major physics background remaining
Semileptonic

\[ \mathcal{R}(J/\psi) = \frac{B(B_c^+ \to J/\psi \tau^+\nu_\tau)}{B(B_c^+ \to J/\psi \mu^+\nu_\mu)} = 0.71 \pm 0.17 \text{ (stat)} \pm 0.18 \text{ (syst)} \]
Belle II
First phase 3 data are being taken as we speak!
Belle II tau

- **Graph**: A plot showing the limit of certain processes over time, with markers for different experiments like CLEO, BaBar, Belle, MEG, etc.

- **Diagram**: A schematic illustrating particle interactions, including symbols for electron and tau, with notations like $\nu_\tau$, $3\pi^\pm + n\pi^0$, and tagged particles.
Belle II LDM
Belle II DP

Work in progress

Proton beam dumps

SN1987A
$g_{a\gamma Z} = 0$

$e^+e^- \rightarrow \gamma\gamma$

Belle II 0.472 fb$^{-1}$
Belle II 135 fb$^{-1}$
LHCb Upgrades
LHCb Upgrades
The LHCb upgrade
The LHCb upgrade

- VELO Silicon Pixels
- RICH MAPMT
- CALO New readout electronics
- New off-detector electronics
- T-Stations Scintillating Fibers
- Muon Detector
- Upstream Tracker
- Vertex Locator
- New detector electronics
RF foil removal will drastically improve vertexing performance

- IP resolution at low $p_T$ nearly doubles, better bkg. suppression
- Fraction of wrong PV association reduced by 30%
- More precise determination of $m^2_{\text{miss}}, q^2, E_l^*$
- Expected trigger efficiency improvement of $\sim 1.5$
Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb$^{-1}$ recorded during Run 2) and for the LHCb Upgrade (50 fb$^{-1}$). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

<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>$\phi_s(B_s^0 \to J/\psi \phi)$ (rad)</td>
<td>0.050</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$\phi_s(B_s^0 \to J/\psi f_0(980))$ (rad)</td>
<td>0.068</td>
<td>0.035</td>
<td>0.012</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$A_{sl}(B_0^0)$ (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>$\phi^{\text{eff}}(B_s^0 \to \phi\phi)$ (rad)</td>
<td>0.15</td>
<td>0.10</td>
<td>0.023</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$\phi_s^{\text{eff}}(B^0 \to K^{*0}\bar{K}^{*0})$ (rad)</td>
<td>0.19</td>
<td>0.13</td>
<td>0.029</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta^{\text{eff}}(B^0 \to \phi K^0_S)$ (rad)</td>
<td>0.30</td>
<td>0.20</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed</td>
<td>$\phi^{\text{eff}}(B_s^0 \to \phi\gamma)$</td>
<td>0.20</td>
<td>0.13</td>
<td>0.030</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td>currents</td>
<td>$\tau^{\text{eff}}(B_s^0 \to \phi\gamma)/\tau_B^0$</td>
<td>5%</td>
<td>3.2%</td>
<td>0.8%</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>$q_0^2 A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$</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>$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^{+}\mu^+\mu^-)$</td>
<td>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$\mathcal{B}(B_0^0 \to \mu^+\mu^-)$ (10$^{-9}$)</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td>Unitarity</td>
<td>$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_0^0 \to \mu^+\mu^-)$</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>triangle</td>
<td>$\gamma(B \to D^{(<em>)}\bar{K}^{(</em>)})$</td>
<td>7°</td>
<td>4°</td>
<td>1.1°</td>
<td>negligible</td>
</tr>
<tr>
<td>angles</td>
<td>$\gamma(B_0^0 \to D^{(<em>)}\bar{K}^{(</em>)})$</td>
<td>17°</td>
<td>11°</td>
<td>2.4°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta(B_0^0 \to J/\psi K^0_S)$</td>
<td>1.7°</td>
<td>0.8°</td>
<td>0.31°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_{T}(D^0 \to K^{+}K^{-})$ (10$^{-4}$)</td>
<td>3.4</td>
<td>2.2</td>
<td>0.5</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>0.12</td>
<td>–</td>
</tr>
<tr>
<td>Observable</td>
<td>Current LHCb</td>
<td>LHCb 2025</td>
<td>Belle II</td>
<td>Upgrade II</td>
<td>ATLAS &amp; CMS</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>--------------</td>
<td>-----------</td>
<td>----------</td>
<td>------------</td>
<td>-------------</td>
</tr>
<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>0.1 274</td>
<td>0.025</td>
<td>0.036</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>$R_{K^*}$ ($1 &lt; q^2 &lt; 6 \text{GeV}^2 c^4$)</td>
<td>0.1 275</td>
<td>0.031</td>
<td>0.032</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td>$R_{\phi}$, $R_{pK}$, $R_{\pi}$</td>
<td>–</td>
<td>0.08, 0.06, 0.18</td>
<td>–</td>
<td>0.02, 0.02, 0.05</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 $B_s^0 \rightarrow D_s^+ K^-$</td>
<td>$(^{+17}_{-28})^\circ$</td>
<td>$4^\circ$</td>
<td>–</td>
<td>1$^\circ$</td>
<td>–</td>
</tr>
<tr>
<td>$\gamma$, all modes</td>
<td>$(^{+50}_{-58})^\circ$</td>
<td>1.5$^\circ$</td>
<td>1.5$^\circ$</td>
<td>0.35$^\circ$</td>
<td>–</td>
</tr>
<tr>
<td>$\sin 2\beta$, with $B^0 \rightarrow J/\psi K_s^0$</td>
<td>0.04 609</td>
<td>0.011</td>
<td>0.005</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>$\phi_s$, with $B_s^0 \rightarrow J/\psi \phi$</td>
<td>49 mrad 44</td>
<td>14 mrad</td>
<td>–</td>
<td>4 mrad 22 mrad 610</td>
<td>–</td>
</tr>
<tr>
<td>$\phi_s$, with $B_s^0 \rightarrow D_s^+ D_s^-$</td>
<td>170 mrad 49</td>
<td>35 mrad</td>
<td>–</td>
<td>9 mrad</td>
<td></td>
</tr>
<tr>
<td>$\phi_s^{s\bar{s}}$, with $B_s^0 \rightarrow \phi \phi$</td>
<td>154 mrad 94</td>
<td>39 mrad</td>
<td>–</td>
<td>11 mrad Under study 611</td>
<td>–</td>
</tr>
<tr>
<td>$a_{1l}$</td>
<td>$33 \times 10^{-4}$</td>
<td>211</td>
<td>$10 \times 10^{-4}$</td>
<td>–</td>
<td>$3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
<td>$</td>
<td>6% 201</td>
</tr>
<tr>
<td>$B_s^0, B^0 \rightarrow \mu^+ \mu^-$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$</td>
<td>90% 264</td>
<td>34%</td>
<td>–</td>
<td>10% 21% 612</td>
<td>–</td>
</tr>
<tr>
<td>$\tau_{B_s^0 \rightarrow \mu^+ \mu^-}$</td>
<td>22% 264</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></td>
</tr>
<tr>
<td><strong>b \rightarrow c \ell^- \bar{\nu}_\ell</strong> LUV studies</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(D^*)$</td>
<td>0.026 215 217</td>
<td>0.0072</td>
<td>0.005</td>
<td>0.002</td>
<td>–</td>
</tr>
<tr>
<td>$R(J/\psi)$</td>
<td>0.24 220</td>
<td>0.071</td>
<td>–</td>
<td>0.02</td>
<td>–</td>
</tr>
<tr>
<td><strong>Charm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta A_{CP}(KK - \pi \pi)$</td>
<td>$8.5 \times 10^{-4}$</td>
<td>$6.13$</td>
<td>$1.7 \times 10^{-4}$</td>
<td>$5.4 \times 10^{-4}$</td>
<td>$3.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>$A_\Gamma$ (\approx x \sin \phi)</td>
<td>$2.8 \times 10^{-4}$</td>
<td>240</td>
<td>$4.3 \times 10^{-5}$</td>
<td>$3.5 \times 10^{-4}$</td>
<td>$1.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>$x \sin \phi$ from $D^0 \rightarrow K^+ \pi^-$</td>
<td>$13 \times 10^{-4}$</td>
<td>228</td>
<td>$3.2 \times 10^{-4}$</td>
<td>$4.6 \times 10^{-4}$</td>
<td>$8.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>$x \sin \phi$ from multibody decays</td>
<td>–</td>
<td>(K3$^\pi$) $4.0 \times 10^{-5}$</td>
<td>(K$^0_s \pi \pi$) $1.2 \times 10^{-4}$</td>
<td>(K$^3 \pi$) $8.0 \times 10^{-6}$</td>
<td>–</td>
</tr>
</tbody>
</table>
WC Fit
Prospect for LHCb Upgrades

Fit to $B \rightarrow K^* \ell \ell$ toy data, assuming the scenario $\Delta C_9 = -\Delta C_{10} = 0.7$
Simultaneous fit of electron and muons allows to cancel theory uncertainty
- Robust experimental procedure since most of the parameters are “fixed” from the high statistics muons —> only two free parameters in the electron sample (in addition to few nuisance parameters)
\[ B^0 \rightarrow K^* \ell^+ \ell^- \] simultaneous fit

- The Amplitude of \( B \rightarrow K^* \ell \ell \) includes all information of angular observables and \( R(K^*) \)

- It is insensitive on theory parameters