LHCb Overview

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With Higgs discovery all SM particles are found, however SM is an incomplete theory (DM, matter-antimatter asymmetry, ...)

However, no signs for BSM physics from direct searches at the LHC so far

Precision searches with flavour probe virtual corrections to the SM FCNC observables can be significantly affected by new heavy BSM particles

Allows to access mass scales well beyond direct searches ($O(100 \text{ TeV})$)

\[ \text{Mass scale (TeV)} \]

From [ATLAS SUSY summary] and [ATLAS Exotics summary], similar plots also from CMS
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Introduction

Flavour Anomalies

Loop-level $b \to s\ell\ell$ FCNCs

- $B^0 \to K^{*0} \mu^+ \mu^-$ angular: $\sim 3.4\sigma$
  [LHCb, JHEP 02 (2016) 104]
- $B(b \to s\mu^+ \mu^-)$: $\sim 3\sigma$
  [LHCb, JHEP 09 (2015) 179]
- LFU in $R_K$, $R_{K^*}$: $2.6\sigma$, $2.4\sigma$
  [LHCb, PRL 113 (2014) 151601] [LHCb, JHEP 08 (2017) 055]

Tree-level $b \to c\tau\nu$ decays

- $R(D)$: $2.3\sigma$ [BaBar, PRL 109 (2012) 101802]
- $R(D^*)$: $3.0\sigma$ [LHCb, PRL 115 (2015) 111803] [LHCb, PRL 120 (2017) 171802]

Combination $\sim 3.8\sigma$

- No single measurement at the level of an observation
- However, interesting pattern emerges
**LHCb: Optimized for precision flavour measurements**

- $b\bar{b}$ produced in forward/backward direction → Optimized acceptance $2 < \eta < 5$
- Huge production cross-sections in LHCb acceptance
  - $1.4 \times 10^{11}$ $b\bar{b}$-pairs per fb$^{-1}$ (Run 2)
- All beauty, charm and strange hadrons produced ($B^0_s, \Lambda_b^0, B^+_c, D^+_s, \Lambda^+_c, \Sigma^+, \ldots$)

<table>
<thead>
<tr>
<th>$\sqrt{s}$ = 7 TeV</th>
<th>$\sqrt{s}$ = 13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{bb}^{\text{acc.}}$ [µb]</td>
<td>$75.3 \pm 14.1$</td>
</tr>
<tr>
<td>$\sigma_{cc}^{\text{acc.}}$ [µb]</td>
<td>$1419 \pm 134$</td>
</tr>
</tbody>
</table>

Refs.:
- [JINST 3 (2008) S08005]
- [IJMPA 30 (2015) 1530022 ]
- [PLB 694:209 (2010)]
- [NPB 871 (2013) 1-20]
- [PRL 118 (2017) 052002]
- [JHEP 03 (2016) 159]
- C. Langenbruch (RWTH), Implications 2018
Heavy flavour signature

$B^0$ mixing

- **Excellent IP resolution** $\sim 20 \mu m$ to identify $B$ decay vertices
- **Decay time resolution** $\sim 45$ fs
- **Resolutions** $\sigma(p)/p = 0.5 - 1\%$, $\sigma(m) \sim 22$ MeV for two-body $B$-decays
- $\rightarrow$ Low combinatorial backgrounds
**The LHCb Detector**

**LHCb: Optimized for precision flavour measurements**

- **Tracking:** Velo, TT, IT+OT
- **Calo:** ECAL, HCAL

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**Cherenkov angle vs. momentum**

![Cherenkov angle vs. momentum graph](image)

**K identification/π misidentification**

![K identification/π misidentification graph](image)

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- Excellent particle identification through RICH detectors and muon system
- High identification efficiencies $\epsilon_{K\rightarrow K} \sim 95\%$, $\epsilon_{\mu\rightarrow \mu} \sim 97\%$
- Low misidentification probabilities $\epsilon_{\pi\rightarrow K} \sim 5\%$, $\epsilon_{\pi\rightarrow \mu} \sim 1 - 3\%$
- Low backgrounds from misidentification

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**The LHCb Detector**

**LHCb: Optimized for precision flavour measurements**

**Tracking:** Velo, TT, IT+OT

**Calo:** ECAL, HCAL

**PID:** RICH1, RICH2, Muon

- Flexible trigger system with low thresholds: $p_T(\mu) > 1.8$ GeV, $E_T(e) > 3.0$ GeV
- High efficiencies, e.g. $\epsilon_{\text{trigger}}(B \rightarrow J/\psi X) \sim 90\%$
- Since Run 2: Online calibration and alignment, allows use of PID in trigger
- Allows low $p_T$ physics: charm, strange, exotica, ...

**LHCb Run 2 trigger**

- 40 MHz bunch crossing rate
- L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures
  - 450 kHz $h^\pm$
  - 400 kHz $\mu/\mu\mu$
  - 150 kHz $e/\gamma$
- Software High Level Trigger
  - Partial event reconstruction, select displaced tracks/vertices and dimuons
  - Buffer events to disk, perform online detector calibration and alignment
  - Full offline-like event selection, mixture of inclusive and exclusive triggers
- 12.5 kHz (0.6 GB/s) to storage

**2016 $\mu\mu$ exotica line [PRL 120 (2018) 061801]**

- Candidates
  - $10^7$
  - $10^6$
  - $10^5$
  - $10^4$
  - $10^3$
  - $10^2$
  - $10$

**LHCb preliminary**

- Prompt Trigger Output
  - $p_T(\mu) > 1$ GeV, $\chi^2(\mu) < 6$, $\chi^2(\mu\mu) < 9$
  - $\mu$-ID neural network $> 0.95$

- $\mu\mu$ ($V_2\chi < 6$, $\mu(IP_2\chi) > 1$ GeV, $\mu(Tp-ID\text{ neural network} > 0.95$

- $\mu^-\mu^+$

- [JINST 3 (2008) S08005]
  - [IJMPA 30 (2015) 1530022]

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C. Langenbruch (RWTH), Implications 2018
LHCb: Optimized for precision flavour measurements

- **Tracking:** Velo, TT, IT+OT
- **PID:** RICH1, RICH2, Muon
- **Calo:** ECAL, HCAL

- $N_{K^*0\mu\mu} = 624\pm30$
- $N_{K^*0\ell\ell} = 50\pm8$
- $N_{K^*0\mu\mu} = 346\pm24\ (+107\pm14)$
- $N_{K^*0\mu\mu} = 275\pm35$

**Performance comparison using $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ Run 1 results as example**

- LHCb compares very favourably
  - Largest yields ($b\bar{b}$ cross-section, large acceptance and high trigger efficiencies)
  - Excellent mass resolution and low combinatorial backgrounds
  - Negligible peaking backgrounds due to powerful particle identification
A wealth of results published with Run 1 data

Several new results published or upcoming include Run 2 data

$> 9 \text{ fb}^{-1}$ data by end of Run 2: Look forward to many exciting new results!

$\rightarrow$ Accounting for $\sigma_{b\bar{b}}$ increase expect gain factor $\sim 5$ of Run 1+2 wrt. Run 1
Upgrade Ia+b: $50 \text{ fb}^{-1}$ after Run 3+4 at $\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

Upgrade II: $300 \text{ fb}^{-1}$ after Run 5+6 at $\mathcal{L} = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

Full Belle 2 detector data taking starting 2019, $50 \text{ ab}^{-1}$ sample 2025
LHCb Upgrade I: $50 \text{ fb}^{-1}$ at $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

- Removal of L0 bottleneck and move to full software trigger will increase efficiencies, by a factor of $\sim 2$ for hadronic modes
- Upgrade I replaces frontend electronics: readout at inelastic 30 MHz rate
- Far reaching detector upgrades to improve occupancy, radiation hardness
  Vertex Locator $\rightarrow$ Pixel; Main trackers $\rightarrow$ SciFi Tracker, UT; RICH photodetectors $\rightarrow$ Replacing 90% of active channels!
LHCb Upgrade I: $50\text{ fb}^{-1}$ at $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

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- Upgrade I replaces frontend electronics: readout at inelastic $30\text{ MHz}$ rate
- Far reaching detector upgrades to improve occupancy, radiation hardness
  - Vertex Locator $\rightarrow$ Pixel; Main trackers $\rightarrow$ SciFi Tracker, UT; RICH photodetectors
  - Replacing 90% of active channels!
Upgrade II will collect $300 \text{ fb}^{-1}$ to fully exploit the flavour physics potential of the HL-LHC

- Pileup of $\sim 50$ requires upgrades to cope with radiation and occupancy
- Use of timing information to separate primary vertices
- Reduced material in Vertex Detector to improve IP resolution
- Studies ongoing for improved ECAL with higher granularity
The CKM matrix elements are given by:

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} =
\begin{pmatrix}
1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8} & -\lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8} (1 + 4A^2) & A\lambda^2 \\
A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 + A\frac{\lambda^4}{2} (1 - 2(\rho + i\eta)) & 1 - A^2 \frac{\lambda^4}{2}
\end{pmatrix} + O(\lambda^5)
\]

- Quark flavour in SM described by 6 couplings and 4 CKM parameters
- $A, \lambda, \rho, \eta$ not predicted by SM, need to be measured

Tree-level constraints and Loop-level constraints are compared.

Still a lot of room for NP → More precise determinations needed.
Determining $\gamma$ from $B^- \rightarrow D^0 K^-$ tree-level decays

- Access $\gamma$ with common $D^0$ final state $f_D$
  1. ADS flavour specific
  2. GLW CP eigenstate
  3. GGSZ Dalitz analysis

- Dalitz plot analysis of $\sim 4500$ $B^- \rightarrow D(K_S^0 h^+ h^-)K^-$ decays ($2 \text{fb}^{-1}$ Run 2)
- Most precise single measurement $\gamma = (87^{+11}_{-12})^\circ$ [JHEP 08 (2018) 176]
LHCb $\gamma$ combination exploits complementarity of inputs

<table>
<thead>
<tr>
<th>$B$ decay</th>
<th>$D$ decay</th>
<th>Method</th>
<th>Ref.</th>
<th>Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-$</td>
<td>GLW</td>
<td>14</td>
<td>Run 1 &amp; 2</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-$</td>
<td>ADS</td>
<td>15</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to h^+\pi^-\pi^+\pi^-$</td>
<td>GLW/ADS</td>
<td>15</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-\pi^0$</td>
<td>GLW/ADS</td>
<td>16</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to K^0_S h^+h^-$</td>
<td>GGSZ</td>
<td>17</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to K^0_S h^+h^-$</td>
<td>GGSZ</td>
<td>18</td>
<td>Run 2</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to K^0_S K^+\pi^-$</td>
<td>GLS</td>
<td>19</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-$</td>
<td>GLW</td>
<td>14</td>
<td>Run 1 &amp; 2</td>
</tr>
<tr>
<td>$B^+ \to DK^{*+}$</td>
<td>$D \to h^+h^-$</td>
<td>GLW/ADS</td>
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<tr>
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<td>$D \to h^+\pi^-\pi^+\pi^-$</td>
<td>GLW/ADS</td>
<td>20</td>
<td>Run 1 &amp; 2</td>
</tr>
<tr>
<td>$B^+ \to DK^{*+}$</td>
<td>$D \to h^+h^-$</td>
<td>GLW/ADS</td>
<td>21</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^0 \to DK^{*0}$</td>
<td>$D \to K^+\pi^-$</td>
<td>ADS</td>
<td>22</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^0 \to DK^{*+}$</td>
<td>$D \to h^+h^-$</td>
<td>GLW-Dalitz</td>
<td>23</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^0 \to DK^{*0}$</td>
<td>$D \to K^0_S \pi^+\pi^-$</td>
<td>GGSZ</td>
<td>24</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^0 \to D_S^{+}K^+$</td>
<td>$D_S^+ \to h^+h^-\pi^+$</td>
<td>TD</td>
<td>25</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^0 \to D_S^{+}\pi^\pm$</td>
<td>$D^+ \to K^+\pi^--\pi^+$</td>
<td>TD</td>
<td>26</td>
<td>Run 1</td>
</tr>
</tbody>
</table>

- LHCb $\gamma$ combination yields $\gamma = \left(74.0^{+5.0}_{-5.8}\right)^\circ$ [LHCb-CONF-2018-002]
- Dominating the world average $\gamma = \left(73.5^{+4.2}_{-5.1}\right)^\circ$ [HFLAV winter 2018]
- Slight tension with loop-determination $\gamma = \left(65.6^{+1.0}_{-3.4}\right)^\circ$ [CKMfitter 2018]
- 3–4° precision with full Run 2, 1.5° with 23 fb$^{-1}$, 0.35° with Upgrade II
Combination $\phi_s = -0.021 \pm 0.031 \text{ rad}$ [HFLAV 2018]

Compare with $\phi_s = -0.037 \pm 0.001 \text{ rad}$ from indirect constraints

Combination dominated by $B^0_s \rightarrow J/\psi \phi$ time-dependent angular analysis by LHCb [PRL 114 (2015) 041801], stat. limited

LHCb Upgrade II expects sensitivity of 0.004 rad with 300 fb$^{-1}$
CP-violation and Mixing

CKM prospects

Inputs

LHCb now

\[ \sin 2\beta \]

\[ \Delta m_d \]

\[ |V_{ub}|/|V_{cb}| \]

LHCb Upgrade Ia 23 fb\(^{-1}\)

\[ \sin 2\beta \]

\[ \Delta m_d \]

\[ |V_{ub}|/|V_{cb}| \]

LHCb Upgrade II 300 fb\(^{-1}\)

\[ \sin 2\beta \]

\[ \Delta m_d \]

\[ |V_{ub}|/|V_{cb}| \]

<table>
<thead>
<tr>
<th>CKM inputs (LHCb)</th>
<th>LHCb (now)</th>
<th>LHCb 23 fb(^{-1})</th>
<th>LHCb 300 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sin 2\beta )</td>
<td>0.760 ± 0.034</td>
<td>0.7480 ± 0.0095</td>
<td>0.7480 ± 0.0024</td>
</tr>
<tr>
<td>( \gamma ) rad</td>
<td>1.296(^{+0.087}_{-0.101})</td>
<td>1.136 ± 0.025</td>
<td>1.136 ± 0.005</td>
</tr>
<tr>
<td>(</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
</tr>
<tr>
<td>( \Delta m_d (\text{ps}^{-1}) )</td>
<td>0.5065 ± 0.0020</td>
<td>same</td>
<td>same</td>
</tr>
<tr>
<td>( \Delta m_s (\text{ps}^{-1}) )</td>
<td>17.757 ± 0.021</td>
<td>same</td>
<td>same</td>
</tr>
</tbody>
</table>

Hadronic input (LQCD)

\[ \xi = \frac{f_{B_d} \sqrt{B_{B_d}}}{f_{B_s} \sqrt{B_{B_s}}} \]

- 0.6\% 0.2\%

LHCb Overview
CP-violation and Mixing

Mixing and CPV in Charm: $y_{CP}$

■ Mixing parameters: $x = \frac{m_2 - m_1}{\Gamma}$, $y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$, $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$

$$y_{CP} = \frac{\Gamma_{CP+}}{\Gamma} - 1 \text{ no CPV}$$

■ Measured using time-dependent ratio between $\pi^+\pi^-$ ($K^+K^-$) and $K^-\pi^+$ yields, using semileptonic tag $\bar{B} \to D^0 \mu^- \bar{\nu}_\mu X$

■ Result: $y_{CP} = (0.57 \pm 0.13 \pm 0.09)\%$ [LHCb-PAPER-2018-038] compatible with current world average $(0.84 \pm 0.16)\%$ and as precise

■ Appearance of this result on the arXiv is imminent!

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Rare FCNC decays are loop-suppressed in the SM

- NP can contribute, affect decay rates and angular distributions
- Model independent description in effective field theory

\[
\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i + \frac{\kappa}{\Lambda_{\text{NP}}^2} O
\]

- Local operator
- Wilson coefficient ("effective coupling")
- NP coupling
- NP scale

- \(i = 1, 2\) Tree
- \(i = 3 - 6, 8\) Gluon penguin
- \(i = 7\) Photon penguin
- \(i = 9, 10\) EW penguin
- \(i = S, P\) (Pseudo)scalar penguin
Loop- and helicity suppressed with purely leptonic final state:
Experimentally and theoretically clean probe of new (pseudo)scalars

First observation of $B_s^0 \rightarrow \mu^+\mu^-$ (7.8 $\sigma$) by single experiment with 4.4 $fb^{-1}$ of data (incl. 1.4 $fb^{-1}$ Run 2) by LHCb [PRL 118 (2017) 191801]:

$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$  \hspace{1cm} $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) = (1.5^{+1.2}_{-1.0}^{+0.2}_{-0.1}) \times 10^{-10}$

Eff. lifetime $\tau(B_s^0 \rightarrow \tau^+\tau^-) = 2.04 \pm 0.44 \pm 0.05$ ps complementary probe

Upgrade II: 4% uncertainty on $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$, 10% on $B^0/B_s^0$ ratio, 2% uncertainty on $\tau$, time-dep. CP-violation $\sigma(S_{\mu\mu}) \sim 0.2$
Branching fractions of rare $b \to s \mu^+ \mu^-$ decays

- **Pattern:** Data consistently below SM predictions
- **But sizeable hadronic theory uncertainties**
- **Tensions at $1 - 3\sigma$ level**
Angular analyses of $b \to s \mu^+ \mu^-$ decays: $P'_5$ and friends

- $B^0 \to K^{*0} (\to K^+ \pi^-) \mu^+ \mu^-$ exhibits rich angular structure, one example the less form-factor dependent observable $P'_5$
- In $q^2$ bins $[4.0, 6.0]$ and $[6.0, 8.0]$ GeV$^2$/c$^4$ local deviations of $2.8\sigma$ and $3.0\sigma$
- LHCb only global $B^0 \to K^{*0} \mu^+ \mu^-$ analysis corresponds to $3.4\sigma$
- Significances depend on hadronic charm-loop uncertainties
- Run 2 update in preparation, $q^2$-unbinned approaches also pursued

$P'_5$ vs. $q^2$ [GeV$^2$/c$^4$]


$B^0 \to K^{*0} \to K^+ \pi^- \mu^+ \mu^-$ exhibits rich angular structure, one example the less form-factor dependent observable $P'_5$

In $q^2$ bins $[4.0, 6.0]$ and $[6.0, 8.0]$ GeV$^2$/c$^4$ local deviations of $2.8\sigma$ and $3.0\sigma$

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Lepton Flavour Universality tests $R_{K^*}$ and $R_K$

$\quad R_X = \int \frac{d\Gamma(B \rightarrow X \mu^+ \mu^-)}{dq^2} \, dq^2 / \int \frac{d\Gamma(B \rightarrow X e^+ e^-)}{dq^2} \, dq^2 \, \text{SM} \equiv 1 \pm O(1\%)$ [EPJC 76 (2016) 8,440]

unaffected by hadronic uncertainties

Numerical result and compatibility with SM prediction(s):

$R_{K^*}(0.045 < q^2 < 1.1 \text{ GeV}^2) = 0.66^{+0.11}_{-0.07} \pm 0.03$ at low $q^2$: $2.1$-$2.3 \sigma$

$R_{K^*}(1.1 < q^2 < 6.0 \text{ GeV}^2) = 0.69^{+0.11}_{-0.07} \pm 0.05$ at central $q^2$: $2.4$-$2.5 \sigma$

$R_K(1 < q^2 < 6.0 \text{ GeV}^2) = 0.745^{+0.090}_{-0.074} \pm 0.036$ at central $q^2$: $2.6 \sigma$
Prospects for rare decays

- $R_K$ and $R_{K^*}$ updates with Run 2 data in preparation, In addition, other $R_X$ will be measured e.g. $R_{pK}$, $R_{\phi}$, $R_{K\pi\pi}$, ...

- Upgrade II samples will reduce $R_K, K^*$ uncertainties below 0%-level

- Huge samples in Upgrade II:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
<th>$K^+\mu^+\mu^-$</th>
<th>$K^{*0}\mu^+\mu^-$</th>
<th>$K^+e^+e^-$</th>
<th>$K^{*0}e^+e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>862 000</td>
<td>435 000</td>
<td>46 000</td>
<td>20 000</td>
</tr>
</tbody>
</table>

- Upgrade II NP reach up to $\mathcal{O}(100 \text{ TeV})$

  Lambda reach factor $\sim 2$ higher than Upgrade Ia
Prospects for rare decays

Integrated Luminosity | $3 \text{ fb}^{-1}$ | $23 \text{ fb}^{-1}$ | $300 \text{ fb}^{-1}$
--- | --- | --- | ---
$R_K$ and $R_{K^*}$ measurements

<table>
<thead>
<tr>
<th></th>
<th>$\sigma(C_9)$</th>
<th>$\Lambda_{\text{tree generic}}$ [TeV]</th>
<th>$\Lambda_{\text{loop generic}}$ [TeV]</th>
</tr>
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<tr>
<td>$\sigma(C_9)$</td>
<td>0.44</td>
<td>40</td>
<td>3</td>
</tr>
<tr>
<td>$\Lambda_{\text{tree generic}}$</td>
<td>0.12</td>
<td>80</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda_{\text{loop generic}}$</td>
<td>0.03</td>
<td>155</td>
<td>2.5</td>
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$B^0 \to K^{*0}\mu^+\mu^-$ angular analysis

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{\text{stat}}(S_i)$</th>
<th>$\Lambda_{\text{tree generic}}$ [TeV]</th>
<th>$\Lambda_{\text{loop generic}}$ [TeV]</th>
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<tr>
<td>$\sigma_{\text{stat}}(S_i)$</td>
<td>0.034–0.058</td>
<td>50</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda_{\text{tree generic}}$</td>
<td>0.009–0.016</td>
<td>75</td>
<td>6</td>
</tr>
<tr>
<td>$\Lambda_{\text{loop generic}}$</td>
<td>0.003–0.004</td>
<td>115</td>
<td>9</td>
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- $R_K$ and $R_{K^*}$ updates with Run 2 data in preparation,
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<th>$K^{*0}e^+e^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>862 000</td>
<td>435 000</td>
<td>46 000</td>
<td>20 000</td>
</tr>
</tbody>
</table>

- Upgrade II NP reach up to $\mathcal{O}(100 \text{ TeV})$
  $\Lambda_{\text{NP}}$ reach factor $\sim 2$ higher than Upgrade Ia
Lepton universality can also be tested in $b \to c \ell \nu$ tree-level decays.

- Modified coupling in particular possible to third generation $\tau$
- Theoretically clean tests possible in $B$ decays:

$$R_{D^*} = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu)} \overset{\text{SM}}{=} 0.252 \pm 0.003$$

- Dependence on $V_{cb}$ cancels in ratio

[PRD 85 (2012) 094025]
LHCb also has access to other $b$-hadron species: $B_s^0$, $B_c^+$, $\Lambda_b^0$, \ldots

So far LHCb has published analyses of

- $R_{D^*} = 0.336 \pm 0.027 \pm 0.030$ with $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$
  compatible with the SM at $2.1 \sigma$ [PRL 115 (2015) 111803]

- $R_{D^*} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$ with $\tau^- \to \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$
  compatible with the SM at $1 \sigma$ [PRL 120 (2018) 171802]

- $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$ using $B_c^+$ decays
  compatible with the SM at $\sim 2 \sigma$ [PRL 120 (2018) 121801]
Semileptonic Decays

$R_D(\ast)$ combination and prospects

- All measurements see excess wrt. SM prediction
- Tension of $R_D/R_D\ast$ combination corresponds to $\sim 3.8 \sigma$
- Run 2 updates ongoing, additional modes in preparation ($R_{D_s}$, $R_{\Lambda_c^+}$, ...)
- Upgrade II will allow angular analysis to determine spin structure of NP
- Profits from vertexing improvements and higher trigger $\epsilon$ in the Upgrade(s)
Many very interesting recent results from spectroscopy, unfortunately no time to go into detail here

Detailed presentations following this talk in the very same session

And many more!
LHCb can be turned into fixed target experiment using SMOG (System for Measuring Overlap with Gas) system [JINST 9 (2014) P12005]

- Originally developed for beam profile measurements for $\mathcal{L}$ determination
- Target: Noble Gas injected close to vertex detector (He, Ne, Ar, ...)
- Allows very useful measurements connected to astroparticle physics
  - AMS-02 and PAMELA measure cosmic ray flux of $\bar{p}$ with high precision
  - Requires knowledge of $\bar{p}$ production in interaction of cosmic rays with interstellar medium (H, He)
LHCb performed first measurement of \( \sigma(p + \text{He} \rightarrow \bar{p} + X) \) at \( \sqrt{s_{NN}} = 110 \text{ GeV} \) [arXiv:1808.06127]

- Exploiting particle identification to separate \( K^-/\pi^-/\bar{p} \)
- Determine \( \sigma \) in bins of \( p \) and \( p_T \)
- Uncertainty < 10\% for most bins, lower than spread from various predictions,
- Result will significantly improve future predictions of \( \bar{p} \) flux
LHCb has shown excellent performance in Run 1 and 2 resulting in large high quality data samples.

The LHCb Physics programme is unique and diverse, far beyond CP violation and rare decays.

Many results in agreement with SM prediction setting strong constraints on NP.

But some intriguing tensions remain, the Flavour anomalies:
- $b \rightarrow s\mu^+\mu^-$ $B$ and angular observables
- LFU tests in rare decays: $R_K$ and $R_{K^*}$
- LFU tests in $b \rightarrow c\ell\nu$ decays: $R_D(\ast)$

Updates with Run 2 data coming soon that will clarify the situation.

Data already on tape corresponds to an effective signal yield increase by factor $\sim 5$ wrt. Run 1.
Outlook

- LHCb well positioned for the future LHC Runs
- Upgrade I will deliver $50 \, fb^{-1}$ that will be essential to precisely study potential deviations, trigger efficiency for hadronic modes increases by a factor 2
- Upgrade II will provide unprecedented $300 \, fb^{-1}$ sample to fully exploit the strength of precision measurements
- Will allow to probe NP scales $\Lambda_{NP}$ a factor $\sim 2$ higher than with the Run 3 sample
- We welcome Belle II joining with full detector soon, increased efforts from ATLAS/CMS very welcome
- Apologies to all results I could not mention due to time
Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current LHCb</th>
<th>LHCb 2025</th>
<th>Belle II</th>
<th>Upgrade II</th>
<th>ATLAS &amp; CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EW Penguins</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{R}_K$ ($1 &lt; q^2 &lt; 6 \text{ GeV}^2 c^4$)</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 $B_s^0 \to D_s^+ K^-$</td>
<td>$(+^{17}_{-22})^\circ$ [136]</td>
<td>$4^\circ$</td>
<td>–</td>
<td>1$^\circ$</td>
<td>–</td>
</tr>
<tr>
<td>$\gamma$, all modes</td>
<td>$(+^{5.0}_{-5.8})^\circ$ [167]</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 $B^0 \to J/\psi K^0_S$</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 $B^0 \to J/\psi \phi$</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 $B^0 \to D^+ D^-$</td>
<td>170 mrad [49]</td>
<td>35 mrad</td>
<td>–</td>
<td>9 mrad</td>
<td>–</td>
</tr>
<tr>
<td>$\phi^{s\bar{s}s}_s$, with $B^0 \to \phi \phi$</td>
<td>154 mrad [94]</td>
<td>39 mrad</td>
<td>–</td>
<td>11 mrad Under study [611]</td>
<td>–</td>
</tr>
<tr>
<td>$a_{s1}$</td>
<td>$33 \times 10^{-4}$ [211]</td>
<td>$10 \times 10^{-4}$</td>
<td>–</td>
<td>$3 \times 10^{-4}$</td>
<td>–</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
<td>$</td>
<td>6% [201]</td>
</tr>
<tr>
<td><strong>$B_s^0, B^0 \to \mu^+ \mu^-$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B^0 \to \mu^+ \mu^-)/B(B_s^0 \to \mu^+ \mu^-)$</td>
<td>90% [264]</td>
<td>34%</td>
<td>–</td>
<td>10% 21% [612]</td>
<td>–</td>
</tr>
<tr>
<td>$\tau_{B_s^0 \to \mu^+ \mu^-}$</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>0.2</td>
<td>–</td>
</tr>
<tr>
<td><strong>$b \to c\ell^- \bar{\nu}_\ell$ LUV studies</strong></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>$8.5 \times 10^{-4}$ [613]</td>
<td>$1.7 \times 10^{-4}$</td>
<td>$5.4 \times 10^{-4}$</td>
<td>$3.0 \times 10^{-5}$</td>
<td>–</td>
</tr>
<tr>
<td>$A_{\Gamma} (\approx x \sin \phi)$</td>
<td>$2.8 \times 10^{-4}$ [240]</td>
<td>$4.3 \times 10^{-5}$</td>
<td>$3.5 \times 10^{-4}$</td>
<td>$1.0 \times 10^{-5}$</td>
<td>–</td>
</tr>
<tr>
<td>$x \sin \phi$ from $D^0 \to K^+ \pi^-$</td>
<td>$13 \times 10^{-4}$ [228]</td>
<td>$3.2 \times 10^{-4}$</td>
<td>$4.6 \times 10^{-4}$</td>
<td>$8.0 \times 10^{-5}$</td>
<td>–</td>
</tr>
<tr>
<td>$x \sin \phi$ from multibody decays</td>
<td>– $(K3\pi)$ $4.0 \times 10^{-5}$ $(K_s^0\pi \pi) 1.2 \times 10^{-4}$ $(K3\pi)$ $8.0 \times 10^{-6}$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
Doubly charmed baryon \( \Xi_{cc}^{++} \) observed for the first time in decay 
\[ \Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \] [PRL 119 (2017) 112001]

Lifetime measured relative to \( \Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^- \pi^+ \) (1.7 fb\(^{-1}\) Run 2) consistent with expectations from weak decay 
\[ \tau(\Xi + cc^{++}) = (0.256^{+0.024}_{-0.022} \pm 0.014) \text{ ps} \] [PRL 121 (2018) 052002]

Recently re-observed in the decay 
\[ \Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+ \] (1.7 fb\(^{-1}\) Run 2) [arXiv:1807.01919]

Combined mass 
\[ m(\Xi_{cc}^{++}) = (3621.24 \pm 0.65 \pm 0.31) \text{ MeV}/c^2 \]
- $\Omega_c$ lifetime least well measured charmed baryon lifetime
- Around 1000 $\Omega_b \rightarrow \Omega_c(\rightarrow pK^-K^-\pi^+)\mu^-\bar{\nu}_\mu X$ decays in 3 fb$^{-1}$
- Lifetime measured relative to $D^+$ from $B \rightarrow D^+(\rightarrow K^-\pi^+\pi^+)\mu^-\bar{\nu}_\mu X$ decays
- $\tau(\Omega_c) = (268 \pm 24_{\text{stat.}} \pm 10_{\text{syst.}} \pm 2_{D\text{ lifetime}})$ fs [PRL 121 (2018) 092003]

- Four times larger, inconsistent with current world average ($69 \pm 12$ fs)