Overview of the LHCb experiment

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8th International conference on High Energy Physics in the LHC Era

9-13 January 2023
Outline

● Introduction to LHCb detector and physics
● Selected recent measurements
  ○ LFU in $b \rightarrow s\ell^+\ell^-$ (for LFU in $b \rightarrow c\ell\nu$ see Iaroslava Bezshyiko's talk)
  ○ CKM structure and CPV in beauty and Charm
  ○ W mass measurement
  ○ Antiproton production in p-He collisions
  ○ Spectroscopy
● A look into the future: the upcoming LHCb upgrade and Upgrade II
Introduction
Why study flavour physics (at hadronic machines)?

It may answer fundamental questions

- Why are there 3 fermion generations? Only 3?
- Hierarchy in Yukawa couplings?
- CPV in quark sector is too small to explain the matter-antimatter asymmetry in the universe. Are there other sources of CPV?
- Flavour physics provides a unique window into new physics through indirect searches (potentially sensitive to higher energy scales than direct searches)
The LHCb Collaboration

- About 1400 scientists, engineers and technicians
- 86 different universities and laboratories from 18 countries
The LHCb detector in Run 1 and Run 2 (2011-2018)

- Excellent particle identification, IP and momentum resolution (~13 µm on the transverse plane and $\Delta p/p \sim 0.5\% - 0.8\%$, respectively.)
- Huge beauty and charm production

$$\sigma(pp \rightarrow b\bar{b}X)_{2<\eta<5} = 144 \pm 1 \pm 21 \mu b$$

$$\sigma(pp \rightarrow c\bar{c}X)_{p_T < 8 \text{ GeV}/c, 2.0 < y < 4.5} = 2369 \pm 3 \pm 152 \pm 118 \mu b.$$
LHCb Trigger System

LHCb 2012 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures
- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu$
- 150 kHz $e/\gamma$

Software High Level Trigger
- Introduce tracking/PID information, find displaced tracks/vertices
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz (0.3 GB/s) to storage
- 2 kHz Inclusive Topological
- 2 kHz Inclusive/Exclusive Charm
- 1 kHz Muon and DiMuon

LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures
- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu$
- 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
Run1 and Run2 data takings

- Running with luminosity levelling at \( \mathcal{L} = 4 \times 10^{32} \text{cm}^{-2} \text{s}^{-1} \), \textbf{2x design luminosity}!
- Roughly 1.5 interactions per bunch crossing
- Total of 9 fb\(^{-1}\) collected
Not just a flavour physics experiment

- Mixing and CP violation in B decays
- Rare B/D/K decays
- Charm decays
- Semileptonic B decays
- Spectroscopy and exotic hadrons
- Hadron production
- Heavy ion physics, fixed target with SMOG
- Electroweak physics, QCD
- Exotics (dark matter, long-lived particles)

More than 600 papers!
Physics Results
Probing NP with $b \to s l^+ l^-$

- Suppressed at tree level, potentially sensitive to NP at the TeV scale
- Dimuonic channels show discrepancies with SM at roughly 3 sigmas in differential decay rates and angular analyses

However charm loops may mimic discrepancies in $C_9$ in angular analysis

LFU tests are theoretically a cleaner probe

From R. Quagliani CERN Seminar

PRL 125, 011802 (2020)

PRL 126, 161802 (2021)

JHEP11(2021)043
LHCb LFU tests (superseded)

- Can NP be generation dependent?
- Measure differential branching fraction vs dilepton invariant mass

\[ R_H \equiv \frac{\int_{q_{\text{max}}^2}^{q_{\text{min}}^2} \frac{dB}{dq^2} (B \to H \mu^+ \mu^-) \, dq^2}{\int_{q_{\text{max}}^2}^{q_{\text{min}}^2} \frac{dB}{dq^2} (B \to H e^+ e^-) \, dq^2} \]

- Experimentally accessible through a double-ratio measurement

\[ R_K = \frac{\mathcal{B} (B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B} (B^+ \to J/\psi (\to \mu^+ \mu^-) K^+)} \times \frac{\mathcal{B} (B^+ \to K^+ e^+ e^-)}{\mathcal{B} (B^+ \to J/\psi (\to e^+ e^-) K^+)} \]

Tension with the SM at 3.1σ
Improved lepton universality measurement

- Simultaneous analysis of $R_K$ and $R_{K^*}$
- Most precise and accurate LFU test in $b\to sll$ transitions
- New data driven treatment of misidentified background

- Dominant systematic from misidentified backgrounds estimation from data driven method
- Measurement still statistically dominated

Details at R. Quagliani CERN Seminar
The CKM matrix

- Describes the transition between quark flavours via weak interaction

\[
V_{\text{CKM}} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} = \begin{pmatrix}
|V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\
-|V_{cd}| & |V_{cs}| & |V_{cb}| \\
|V_{td}|e^{-i\beta} & |V_{ts}|e^{i\beta} & |V_{tb}|
\end{pmatrix}
\]

\[
= \begin{pmatrix}
1 - \lambda^2/2 - \lambda^4/8 \\
-\lambda + A^2\lambda^5 [1 - 2(\rho + i\eta)] / 2 \\
A\lambda^3 \left[1 - (\rho + i\eta)(1 - \lambda^2/2)\right]
\end{pmatrix}
\begin{pmatrix}
\lambda \\
1 - \lambda^2/2 - \lambda^4(1 + 4A^2)/8 \\
-A\lambda^2 + A\lambda^4 [1 - 2(\rho + i\eta)] / 2
\end{pmatrix}
\begin{pmatrix}
A\lambda^3 (\rho - i\eta) \\
A\lambda^2 \\
1 - A^2\lambda^4/2
\end{pmatrix} + O(\lambda^6)
\]

Wolfenstein parametrisation
\[
\lambda = \sin (\theta_c) \approx 0.22, \quad \eta \approx 0.3
\]

- Unitarity conditions \(\rightarrow\) unitarity triangles

\[
V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0
\]

\[
V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0
\]
The CKM matrix

- Describes the transition between quark flavours via weak interaction

\[ V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ -|V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta} & |V_{tb}| \end{pmatrix} \]

\[
= \left( \begin{array}{ccc}
1 - \lambda^2/2 - \lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda + A^2\lambda^5 [1 - 2(\rho + i\eta)]/2 & 1 - \lambda^2/2 - \lambda^4(1 + 4A^2)/8 & A\lambda^2 \\
A\lambda^3 \left[ 1 - (\rho + i\eta)(1 - \lambda^2/2) \right] & -A\lambda^2 + A\lambda^4 [1 - 2(\rho + i\eta)]/2 & 1 - A^2\lambda^4/2 \\
\end{array} \right) + \mathcal{O}(\lambda^6)
\]

- 3 quark generations allow for CPV through the phase \( \eta \)
- **Due to the CKM structure the B system is favourable for CPV studies**, on the contrary, CPV in the Charm sector is predicted to be small since amplitudes are dominated by the first two generations

\[ \lambda = \sin(\theta_c) \approx 0.22, \quad \eta \approx 0.3 \]
CKM $\gamma$ angle from $B^\pm \rightarrow D(\rightarrow K\pi\pi\pi\pi)K^\pm$

- Precision measurements of the consistency of the unitarity triangles are a powerful tests of the SM.
- Recent LHCb measurement with the full dataset

$$\frac{\Gamma (B^\pm \rightarrow D [K^+\pi^+\pi^+\pi^+\pi^+] \ K^\pm)}{\Gamma (B^\pm \rightarrow D [K^+\pi^+\pi^+\pi^+\pi^+] \ K^\pm)} = \frac{r_{K3\pi}^2 + (r_B^K)^2 + 2r_{K3\pi}r_B^K R_{K3\pi} \cos(\delta_B^K + \delta_{K3\pi} \pm \gamma)}{1 + (r_{K3\pi}r_B^K)^2 + 2r_{K3\pi}r_B^K R_{K3\pi} \cos(\delta_B^K - \delta_{K3\pi} \pm \gamma)}$$

$\gamma = (54.8^{+6.0}_{-5.8}\text{(stat.)}^{+0.6}_{-0.6}\text{(syst.)}^{+6.7}_{-4.3}\text{(ext.)})$°

Second most precise single-channel determination!
**γ combination**

A combination of all LHCb γ determinations (+ charm mixing and asymmetries)

<table>
<thead>
<tr>
<th>B decay</th>
<th>D decay</th>
<th>Ref.</th>
<th>Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \to Dh^\pm$</td>
<td>$D \to h^+h^-$</td>
<td>[29]</td>
<td>Run 1&amp;2</td>
</tr>
<tr>
<td>$B^\pm \to Dh^\pm$</td>
<td>$D \to h^+\pi^+\pi^-$</td>
<td>[30]</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^\pm \to Dh^\pm$</td>
<td>$D \to K^+\pi^+\pi^-$</td>
<td>[18]</td>
<td>Run 1&amp;2</td>
</tr>
<tr>
<td>$B^\pm \to Dh^\pm$</td>
<td>$D \to h^+h^-\pi^0$</td>
<td>[19]</td>
<td>Run 1&amp;2</td>
</tr>
<tr>
<td>$B^\pm \to Dh^\pm$</td>
<td>$D \to K^0_S h^+h^-$</td>
<td>[31]</td>
<td>Run 1&amp;2</td>
</tr>
<tr>
<td>$B^\pm \to Dh^\pm$</td>
<td>$D \to K^0_S K^+\pi^+$</td>
<td>[32]</td>
<td>Run 1&amp;2</td>
</tr>
<tr>
<td>$B^\pm \to D^*h^\pm$</td>
<td>$D \to h^+h^-$</td>
<td>[29]</td>
<td>Run 1&amp;2</td>
</tr>
<tr>
<td>$B^\pm \to DK^{\pm\pm}$</td>
<td>$D \to h^+h^-$</td>
<td>[33]</td>
<td>Run 1&amp;2(*)</td>
</tr>
<tr>
<td>$B^\pm \to DK^{\pm\pm}$</td>
<td>$D \to h^+\pi^-\pi^+$</td>
<td>[33]</td>
<td>Run 1&amp;2(*)</td>
</tr>
<tr>
<td>$B^\pm \to Dh^\pm\pi^+\pi^-$</td>
<td>$D \to h^+h^-$</td>
<td>[34]</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^0 \to DK^{*0}$</td>
<td>$D \to h^+h^-$</td>
<td>[35]</td>
<td>Run 1&amp;2(*)</td>
</tr>
<tr>
<td>$B^0 \to DK^{*0}$</td>
<td>$D \to h^+\pi^-\pi^+$</td>
<td>[35]</td>
<td>Run 1&amp;2(*)</td>
</tr>
<tr>
<td>$B^0 \to DK^{*0}$</td>
<td>$D \to K^0_S\pi^+\pi^-$</td>
<td>[36]</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^0 \to DK^{*0}$</td>
<td>$D \to K^0_S\pi^-\pi^-$</td>
<td>[36]</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^0 \to D^+\pi^+$</td>
<td>$D^+ \to K^-\pi^+\pi^+$</td>
<td>[37]</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^+ \to D^+K^-$</td>
<td>$D^+_\pi^- \to h^+h^-\pi^+$</td>
<td>[38]</td>
<td>Run 1</td>
</tr>
<tr>
<td>$B^0 \to D^+_\pi^- K^-$</td>
<td>$D^+_\pi^- \to h^+h^-\pi^+$</td>
<td>[39]</td>
<td>Run 1&amp;2</td>
</tr>
</tbody>
</table>

In agreement with previous and global determinations, statistically limited
Observation of CPV in charm with $\Delta A_{CP}$

- CPV in charm predicted small in SM $O(10^{-4})$
- Full Run 1 + Run 2 dataset, $D^*$ and semileptonic tag
- Observable is mainly sensitive to direct CPV
  \[
  \Delta A_{CP} = A_{CP}(D^0 \rightarrow K^+ K^-) - A_{CP}(D^0 \rightarrow \pi^+ \pi^-)
  \]
  assuming universal $a_{CP}^{ind}$
  \[
  \simeq \Delta a_{CP}^{dir} + \frac{\Delta \langle t \rangle}{\tau D^0} a_{CP}^{ind}
  \]
  \[
  \Delta \langle t \rangle = \langle t \rangle_{KK} - \langle t \rangle_{\pi \pi}
  \]
- Experimentally robust as production and detection asymmetries cancel to first order
- Additional measurements are needed to have a better understanding!

$\Delta a_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$

CP violation observed at 5.3$\sigma$!
Time-integrated $CP$ asymmetry in $D^0 \rightarrow K^- K^+$ decays

- Measuring time integrated asymmetries of single channels is much harder
  
  $$A_{CP}(f) = \frac{\Gamma(M \rightarrow f) - \Gamma(M \rightarrow \bar{f})}{\Gamma(M \rightarrow f) + \Gamma(M \rightarrow \bar{f})} = \frac{1 - |A_f/A_f|^2}{1 + |A_f/A_f|^2}$$

- However the observable is the yield asymmetry, which must be corrected for to extract the physical asymmetry

  $$A_{raw} = \frac{N(D \rightarrow f) - N(\bar{D} \rightarrow \bar{f})}{N(D \rightarrow f) + N(\bar{D} \rightarrow \bar{f})} = A_{CP} + A_P + A_D$$

  - $A_P$ is the production asymmetry in pp collisions
  - $A_D$ is the detection asymmetry due to the detector

- $A_P$ and $A_D$ have to be determined and corrected for using calibration samples
Time-integrated $CP$ asymmetry in $D^0 \rightarrow K^- K^+$ decays

- Measurement from LHCb using the full Run 2 dataset

$$A_{CP}(K^- K^+) = [6.8 \pm 5.4 \text{ (stat)} \pm 1.6 \text{ (syst)}] \times 10^{-4}. $$

In combination with $\Delta A_{CP}$

$$a_{K^- K^+}^d = (7.7 \pm 5.7) \times 10^{-4},$$

$$a_{\pi^- \pi^+}^d = (23.2 \pm 6.1) \times 10^{-4},$$

Measurements statistically limited, exciting times for Charm CPV with ongoing and future upgrades
Not only flavour
W boson mass measurement

- First LHCb measurement of W mass, 1.7 fb\(^{-1}\) of 13 TeV data
- Anti-correlation in PDF uncertainties wrt ATLAS and CMS

Excellent prospects for a full Run2 analysis
Measurement of antiproton production

- Looks at p-He (SMOG) data in hyperon decays
- Measure proton-antiproton ratio from hyperon decays
- Extremely useful for the interpretation of results from space-based experiments
- Dominant $\Lambda$ component measured exclusively

SMOG: System for Measuring Overlap with Gas

- Noble gas (He, Ne, Ar) injected into the LHC vacuum around the LHCb interaction region
- Energy between SPS and RHIC
Exotic hadrons, tetra/penta-quarks

J/ψΛ structure at 4.338 GeV in $B^-\rightarrow J/ψΛp^-$ decays
Consistent with a pentaquark candidate with strangeness

Full list and more plots at this link
The LHCb Upgrade
The upgraded LHCb

- Aim to collect \( \sim 50 \text{ fb}^{-1} \) at roughly \( \mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \)
- Keeping at least the same performance on Run 1&2

From L. Dufour talk at MIAMI2022
The upgrade DAQ and trigger

Fully software trigger, overcomes L0 rate limitations in Run1&2 and builds on the successes of Run1 and Run2 (e.g. real time alignment and calibration)
Installation and commissioning of the upgraded detector
First mass peaks!

Now working hard on understanding the new detector and improving calibration and alignment.
LHCb in Run 5&6 ?

- Target: $\sim 300$ fb$^{-1}$
- Pile-up: $\sim 40$
- 200 Tb/second data produced
- To keep the same performance in more difficult conditions, timing will be required in some sub-detectors
- A lot of R&D on new technologies
- Sub-detector TDRs expected after Run 3
What could be achieved in Upgrade II?

- $\sin 2\beta$ vs $|\Delta m|/|\Delta n_s|
- $\sin 2\beta$ vs $|\Delta m|/|\Delta n_s|

- $B^0 \rightarrow D_s^+ D_s^-$
- $B^0 \rightarrow J/\psi K^-$
- $B^0 \rightarrow J/\psi K^+ K^-$ high mass

- $\Delta C_{10}$ vs $\Delta C_9$

Current LHCb Data
Projection for the SM
Projection for a vector-axial-vector NP contribution
Projection for a pure vector NP contribution

Contours drawn at 3$\sigma$

- $\sigma(\phi_s)$ vs Integrated Luminosity [fb$^{-1}$]
- 2, 10, 100, 1000

Solid (dashed) contours contain 68.3% (95.4%)
Conclusions

- LHCb brought many interesting results in Run 1&2, with world leading measurements in the flavour sector
- LHCb showed capabilities that go well beyond its design (e.g. EW physics, heavy ions, etc.)
- I could only show a small fraction of its physics output!
- Now focused on Run3 to get the new detector in shape to acquire an even larger dataset (not just in size but also in physics reach!)
- We are also thinking at the far future and started R&D towards an even more capable detector!
Backups
Track types in LHCb
Trigger yield vs lumi in Run 1&2
Physics performance projections

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current LHCb (up to 9 fb⁻¹)</th>
<th>Upgrade I (23 fb⁻¹)</th>
<th>Upgrade II (50 fb⁻¹)</th>
<th>Upgrade III (300 fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CKM tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma (B \to DK, \text{ etc.})$</td>
<td>$4^\circ$ [9,10]</td>
<td>$1.5^\circ$</td>
<td>$1^\circ$</td>
<td>$0.35^\circ$</td>
</tr>
<tr>
<td>$\phi_8 (B_s^0 \to J/\psi\phi)$</td>
<td>32 mrad [8]</td>
<td>14 mrad</td>
<td>10 mrad</td>
<td>4 mrad</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>/</td>
<td>V_{cb}</td>
<td>(A^0_\mu \to p\mu^-\bar{\nu}_\mu, \text{ etc.})$</td>
</tr>
<tr>
<td>$\alpha_d^A (B^0 \to D^-\mu^+\nu_\mu)$</td>
<td>$36 \times 10^{-4}$ [34]</td>
<td>$8 \times 10^{-4}$</td>
<td>$5 \times 10^{-4}$</td>
<td>$2 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\alpha_d^A (B_s^0 \to D_s^-\mu^+\nu_\mu)$</td>
<td>$33 \times 10^{-4}$ [35]</td>
<td>$10 \times 10^{-4}$</td>
<td>$7 \times 10^{-4}$</td>
<td>$3 \times 10^{-4}$</td>
</tr>
<tr>
<td><strong>Charm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta A_{CP} (D^0 \to K^+K^-, \pi^+\pi^-)$</td>
<td>$29 \times 10^{-5}$ [5]</td>
<td>$13 \times 10^{-5}$</td>
<td>$8 \times 10^{-5}$</td>
<td>$3.3 \times 10^{-5}$</td>
</tr>
<tr>
<td>$A_R (D^0 \to K^+K^-, \pi^+\pi^-)$</td>
<td>$11 \times 10^{-5}$ [38]</td>
<td>$5 \times 10^{-5}$</td>
<td>$3.2 \times 10^{-5}$</td>
<td>$1.2 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\Delta x (D^0 \to K^0_{\pi^+\pi^-})$</td>
<td>$18 \times 10^{-5}$ [37]</td>
<td>$6.3 \times 10^{-5}$</td>
<td>$4.1 \times 10^{-5}$</td>
<td>$1.6 \times 10^{-5}$</td>
</tr>
<tr>
<td><strong>Rare Decays</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$B(B^0 \to \mu^+\mu^-)/B(B_s^0 \to \mu^+\mu^-)$</td>
<td>69% [40,41]</td>
<td>41%</td>
<td>27%</td>
<td>11%</td>
</tr>
<tr>
<td>$S_{uu} (B_s^0 \to \mu^+\mu^-)$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$A^{(2)}_{CP} (B^0 \to K^{*0}e^+e^-)$</td>
<td>0.10 [52]</td>
<td>0.060</td>
<td>0.043</td>
<td>0.016</td>
</tr>
<tr>
<td>$A_{HF} (B^0 \to K^{*0}e^+e^-)$</td>
<td>0.10 [52]</td>
<td>0.060</td>
<td>0.043</td>
<td>0.016</td>
</tr>
<tr>
<td>$A_{\phi} (B_s^0 \to \phi\gamma)$</td>
<td>+0.44 [-0.44] [51]</td>
<td>0.124</td>
<td>0.083</td>
<td>0.033</td>
</tr>
<tr>
<td>$S_{\phi\gamma} (B_s^0 \to \phi\gamma)$</td>
<td>0.32 [51]</td>
<td>0.093</td>
<td>0.062</td>
<td>0.025</td>
</tr>
<tr>
<td>$\alpha_{\gamma} (A^0_s \to \gamma)$</td>
<td>+0.17 [-0.29] [53]</td>
<td>0.148</td>
<td>0.097</td>
<td>0.038</td>
</tr>
<tr>
<td><strong>Lepton Universality Tests</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>$R_K (B^+ \to K^{+}\ell^+\ell^-)$</td>
<td>0.044 [12]</td>
<td>0.025</td>
<td>0.017</td>
<td>0.007</td>
</tr>
<tr>
<td>$R_K (B^0 \to K^{*0}\ell^+\ell^-)$</td>
<td>0.12 [61]</td>
<td>0.034</td>
<td>0.022</td>
<td>0.009</td>
</tr>
<tr>
<td>$R(D^<em>) (B^0 \to D^</em>-\ell^+\nu_\ell)$</td>
<td>0.026 [62,64]</td>
<td>0.007</td>
<td>0.005</td>
<td>0.002</td>
</tr>
</tbody>
</table>
LFU $q^2$ regions

low-$q^2$ region: $0.1 < q^2 < 1.1$ GeV$^2$/c$^4$,

central-$q^2$ region: $1.1 < q^2 < 6.0$ GeV$^2$/c$^4$,

electron $J/\psi$ region: $6 < q^2 < 11$ GeV$^2$/c$^4$, $|m(\ell^+\ell^-) - M_{J/\psi}^{PDG}| < 100$ MeV/c$^2$,

muon $J/\psi$ region: $11 < q^2 < 15$ GeV$^2$/c$^4$, $|m(\ell^+\ell^-) - M_{\psi(2S)}^{PDG}| < 100$ MeV/c$^2$,

electron $\psi(2S)$ region:

muon $\psi(2S)$ region:
Challenges in LFU tests: electrons and energy losses

- Brem recovery is $O(50\%)$ efficient
- Well described in simulation
- Wider fit range than muons
  - more background,
  - more sensitive to peaking structures
  - lineshapes are brem-dependent
Simple backgrounds from double-misidentification can be isolated inverting PID criteria (close to nominal selection) after full selection (i.e. $K^{+,*0}h^+h^-$) on electron mode.

- Similar structures (see backup) also for $R_{K^*}$, however unknown Dalitz for $K^{*0}h^+h^-$
- Single misidentification background as well, often unknown
- Developed a new inclusive data-driven treatment of misidentified background
Mass fit to rare mode electrons: simultaneous fit $R_{K,K^{*0}}$

**low-$q^2$**

- $LHCb$ 9 fb$^{-1}$
- $R_K$ low-$q^2$
- $m(K^+e^+e^-)$ [MeV$/c^2$]
- Data, Total, Signal, Combinatorial, Misidentification, Partially Recoded
- $B^+ \to K^+\eta'(\to e^+e^-\gamma)$

**central-$q^2$**

- $LHCb$ 9 fb$^{-1}$
- $R_K$ central-$q^2$
- $m(K^+e^+e^-)$ [MeV$/c^2$]
- Data, Total, Signal, Combinatorial, Misidentification, Partially Recoded
- $B^+ \to K^+\eta'(\to e^+e^-\gamma)$

**resonant-$J/\psi$**

- $LHCb$ 9 fb$^{-1}$
- $R_K$ J/$\psi$-control
- $m(K^+e^+e^-)$ [MeV$/c^2$]
- Data, Total, Signal, Combinatorial, Misidentification, Partially Recoded
- $B^+ \to K^{*0}\eta/\psi$
- $B^+ \to \pi^{0}J/\psi$
- $K - \pi$ swap

From R. Quagliani CERN Seminar