LHCb dimuon and charm mass distributions

The LHCb collaboration

Abstract

This note presents a collection of mass distributions for dimuons and charm hadrons collected by the LHCb experiment between 2011 and 2015. 1.2 billion dimuons and 1.4 billion charm hadrons have been collected during this data-taking period.
1 Introduction

The LHCb experiment is the dedicated flavour physics experiment at the LHC. Its versatile trigger has a high efficiency for $pp$ collision events containing flavoured hadrons. Its forward acceptance allows for high-precision production measurements sensitive to the effects of quantum chromodynamics. This note presents several mass distributions for events containing two muons or a charm hadron candidate. The dimuon mass distribution can be compared to those presented by the ATLAS and CMS collaborations [1,2].

The data presented in this note was recorded between 2011 and 2015. During Run 1 of the LHC, in 2011 (2012) LHCb recorded $pp$ collisions at a centre-of-mass energy of 7 (8) TeV, corresponding to an integrated luminosity of 1 (2) fb$^{-1}$. During Run 2, which began in 2015, the centre-of-mass energy was increased to 13 TeV. Data corresponding to 0.3 fb$^{-1}$ was recorded in 2015. The distributions presented here have a very weak dependence on the collision energy and thus datasets are combined in some figures. Several billion events containing charm hadrons or pairs of muons have been collected by LHCb to date.

2 Detector and Trigger

The LHCb detector [3,4] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing $b$ or $c$ quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the $pp$ interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The polarity of the dipole magnet is reversed periodically throughout data-taking. The configuration with the magnetic field vertically upwards, UP (downwards, DOWN), bends positively (negatively) charged particles in the horizontal plane towards the centre of the LHC ring. The tracking system provides a measurement of momentum, $p$, of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/$c$. The minimum distance of a track to a primary vertex (PV), the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T)$ µm, where $p_T$ is the component of the momentum transverse to the beam, in GeV/$c$. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [5]. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [6].

The online event selection is performed by a trigger [7], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. In addition, a small fraction of trigger-unbiased events is retained.
3 The dimuon mass distribution

Pairs of muons are either selected during offline processing by an algorithm which has been used for various cross-section measurements [8–12], or are taken from a downscaled sample of minimum-bias triggers.

In the offline selection, the dimuon candidates are built from oppositely-charged tracks that have hits in the muon system. The tracks are required to be of good quality and have a transverse momentum in excess of 650 MeV/c. The two-particle system must have a mass in excess of 3 GeV/c² and a vertex fit $\chi^2$ below 20.

A downscaled sample of minimum-bias triggers is used to obtain dimuons with masses below 3 GeV/c². The same selection as described above is run offline, with the mass requirement removed and the muon transverse momentum requirement set to 100 MeV/c. This approximately corresponds to the kinematic limit imposed by the LHCb acceptance.

To reduce the fraction of mis-identified hadrons, it is additionally required that the muons are well identified with a likelihood in excess of 40% and have a likelihood of being fake below 10% [4]. These additional requirements remove three quarters of the dimuon candidates for little loss of signal $J/\psi$, $\Upsilon$ and $Z$ resonances. Mass distributions without these requirements are shown in Appendix A.

In the offline processing, reconstructed particles are associated with trigger decisions. Selection requirements can therefore be made on whether the decision was due to the signal candidate, other particles produced in the $pp$ collision, or a combination of both. The following families of decisions are considered:

**Single muon:** Several trigger lines select events based on the detection of a single muon and are used for electroweak physics [13,14] and studies of semileptonic $b$-hadron decays [15,16].

The properties of the muon are required to satisfy either of two sets of criteria:

1. high transverse momentum ($p_T > 4.8$ GeV/c), or
2. moderate transverse momentum ($p_T > 1.3$ GeV/c) and detachment from all PVs.

In some data samples, moderate downscales (usually 50%) were applied to these lines, where a random fraction of the data was rejected. Downscaled lines with looser $p_T$ or IP requirements were also run.

**Charmonium:** Several trigger lines dedicated to production studies of $J/\psi$ and $\psi(2S)$ mesons [8–11] decaying to two muons are used. They require two well reconstructed tracks that have hits in the muon system, form a common vertex, and have momentum higher than 6 GeV/c. The lines differ by the mass window and $p_T$ requirements. Dimuons within 100 MeV/c² of the $J/\psi$ ($\psi(2S)$) mass are kept if they have $p_T > 2 (3.5)$ GeV/c. Lines without the $p_T$ requirement are also run with a 10 to 20% downsacle.

This category also contains lines selecting dimuons which are inconsistent with having originated from any PV. They are used in all analyses involving decays of $b$-hadrons to $J/\psi$ and $\psi(2S)$ mesons (e.g. Refs. [17–21]). Similar lines also select dimuons at lower masses for studies of electroweak penguin decays [22].
**Figure 1**: Dimuon mass distribution divided by trigger groups (see text) for Run 1 and 2015 data. An inset plot with a zoom on the bottomonium region is shown on the top right corner.

**Bottomonium**: Pairs of two well reconstructed tracks that have hits in the muon system, form a common vertex, have momentum higher than 6 GeV/c and a mass greater than 4.7 GeV/c² are recorded. These dimuons are used for measurements such as $\Upsilon$ production [12] and $B \to \mu^+ \mu^-$ searches [23].

**Other triggers**: This category contains dimuons that are linked to any trigger line other than those used in the groups above, or were not used in making any positive trigger decision. The main contributor in the region 3–4.7 GeV/c² is the topological trigger [24], which searches for topologies consistent with coming from a $b$-hadron decay. Decays of $b$-hadrons to many final state particles are selected with the topological trigger [22,25,26]. Minimum-bias triggers dominate the region below 3 GeV/c.

Dimuons can be selected by several trigger lines. The categories are filled in the order listed above, meaning a dimuon triggered by a single muon line will not feature in the other categories. In particular, $Z$ bosons are almost all selected by both the single muon and the bottomonium lines. Due to the ordering, they will be featured in the single muon category, which is the cause of the apparent absence of dimuons from the bottomonium category at high masses.

The mass histogram shown in Figs. 1–3 have 1850 bins of variable width, starting at 1 MeV/c² at masses of 0.2 GeV/c². The bin width is then kept approximately proportional to the bin centre, up to a width of 280 MeV/c² at a dimuon mass of 400 GeV/c². The bin contents are scaled such that the number of dimuon candidates per GeV/c² is shown. Therefore the sum of the bin contents does not correspond to the number of dimuon
Figure 2: Dimuon mass distribution divided by trigger groups (see text) for 2011 and 2012 data. An inset plot with a zoom on the bottomonium region is shown on the top right corner.

Figure 3: Dimuon mass distribution divided by trigger groups (see text) for 2015 data. An inset plot with a zoom on the bottomonium region is shown on the top right corner.
candidates, but the integral of the histogram does. The histogram is shown with logarithmic \( x \) and \( y \) scales. The main resonances decaying to two muons are indicated by labels. The small bump around 2 GeV/c\(^2\) is due to \( D^0 \to K^-\pi^+ \) decays where both final-state hadrons decay in flight to muons, or are mis-identified. The rare decays \( \eta \to \mu^+\mu^- \) and \( B^0_s \to \mu^+\mu^- \) are not visible. Charge-conjugated decays are implied throughout this note.

There are 1.17 billion dimuons in Fig. 1, which shows Run 1 and 2015 data. These two samples are shown separately in Figs. 2 and 3. The distributions differ due to the large minimum-bias sample taken in July 2015 and the re-tuned topological trigger lines which reduced the importance of the “other triggers” category in Run 2 above masses of 4.7 GeV/c\(^2\). More sub-samples are shown in Appendix A.

4 Charm hadron mass distributions

Mass distributions of the following high-yield charm hadron decays are presented in this section: \( D^0 \to K^-\pi^+, D^0 \to K^-K^+, D^+ \to K^-\pi^+\pi^+, D^+_s \to K^-K^+\pi^+, D^{*+} \to D^0\pi^+ \) and \( \Lambda_c^+ \to pK^-\pi^+. \) Throughout this note \( D^{*+} \) stands for the \( D^{*+}(2010)^+ \) meson.

4.1 Charm hadrons in Run 1

In the Run 1 (2011–12) dataset, charm hadrons are reconstructed during offline processing by dedicated algorithms which have been used in precision charm physics measurements \cite{27}.

Pion, kaon and proton candidates are required to have \( p_T \) in excess of 200 MeV/c, be inconsistent with having originated from any PV, and fulfil loose particle identification requirements. Two or three particles are combined to form \( D^0, D^+, D^+_s \) and \( \Lambda_c^+ \) candidates according to the decays listed above. The vertex must be of good quality and separated from any PV by more than 100 \( \mu m \). The candidate charm hadron must have a \( p_T \) in excess of 3 GeV/c.

For \( D^{*+} \) mesons, \( D^0 \to K^-\pi^+ \) candidates are selected as described above, except for a looser \( p_T \) requirement of 2 GeV/c. They are combined with any good quality track of the same charge as the child pion from the \( D^0 \) decay. The \( D^{*+} \) candidates must have a good quality vertex and a mass difference \( \Delta m = m_{K^-\pi^+\pi^+} - m_{K^-\pi^+} \) below 155 MeV/c\(^2\).

The hadron candidates are not required to have been selected by any particular trigger offline, however most candidates do fire dedicated trigger lines that apply requirements similar to those listed above, with the exception of particle identification. These triggers require that at least one of the final-state particles has \( p_T > 1.7 \) GeV/c in the 7 TeV data or \( p_T > 1.6 \) GeV/c in the 8 TeV data.

The resulting mass distributions are shown in Fig. 4. Similar distributions split by year and dipole magnet polarity can be found in Appendix B. The signal yield of each distribution is estimated with a binned fit. The signal is modelled by a Gaussian distribution with asymmetric exponential tails. The mass distribution of the combinatorial background in the \( D^0, D^+, D^+_s \), and \( \Lambda_c^+ \) samples is modelled by a second-order polynomial. The \( \Delta m \) distribution for combinatorial background \( D^{*+} \) candidates is modelled as an empirically derived threshold function \cite{28} with a turn-on parameter that is fixed to the known charged pion mass \cite{29}. For \( D^0 \to K^-K^+ \) and \( D^+_s \to K^-K^-\pi^+ \) candidates
an additional component is added to account for backgrounds from $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ decays where a pion is mis-identified as kaon. The same functional form as for the signal is used. All fit parameters are determined from the data. In Fig. 4, the sum of the background components is shown in red. The relative amount of combinatorial background is larger for $\Lambda_c^+$ candidates, because of looser particle identification cuts for protons.

4.2 Charm hadrons in Run 2

The charm hadron selection for Run 2 of the LHC uses a new scheme for the LHCb software trigger [30] which was introduced in 2015 and used in cross-section measurements with 13 TeV data [28,31]. Alignment and calibration is performed in near real-time [30] and updated constants are made available for the trigger [32]. The same alignment and calibration information is propagated to the offline reconstruction, ensuring consistency of high-quality particle identification information between the trigger and offline software.

Improvements to the trigger software and greater computing resources available compared to Run 1 also allow for the convergence of the online and offline track reconstruction, such that offline performance is achieved in the trigger. The identical performance of the online and offline reconstruction offers the opportunity to perform physics analyses directly using candidates reconstructed in the trigger. The storage of only the triggered candidates and the removal of the detector readout information enables a reduction in the event size by an order of magnitude. The selection requirements are similar to those for Run 1 data described in Sec. 4.1.

In 2015, there were two distinct data-taking periods. During the start-up period in July, the trigger settings were optimised for cross-section measurements [28,31]. A random sampling was used at the hardware stage. In the software stage, only lines dedicated to cross-section measurements were run and many requirements were loosened.

From August 2015 onward, data collection for LHCb’s main flavor physics programme was resumed. Only $D^0$ trigger candidates associated to a $D^{*+}$ were saved during this period.

The charm hadrons collected during 2015 are shown in Fig. 5. The $D^0 \to K^-\pi^+$ candidates were only obtained during July. The $D^0 \to K^-K^+$ decay is not shown due to too low yields. The shown fit is identical to that used for Run 1 data. The background level is larger compared to Run 1 data because of the looser selection requirements applied in the trigger. Finally, Fig. 6 combines Run 1 and 2015 data.

In total 1.15 billion charm hadrons have been collected in Run 1 and 290 million in 2015, conservatively assuming full overlap of the $D^{*+} \to D^0\pi^+$ and $D^0 \to K^-\pi^+$ samples when both are collected. The detailed numbers can be found in Appendix B.

5 Conclusion

The LHCb experiment recorded several billion events containing charm hadrons or pairs of muons. Such events are important to monitor the overall performance of the experiment. Thanks to the trigger scheme introduced in Run 2, the recorded yields of dimuons and charm hadrons per unit luminosity have significantly increased. This will allow for more high-precision charm and beauty measurements.
Figure 4: Charm hadron mass distributions for Run 1 data. The (red) solid shape shows the background component of the fit.
Figure 5: Charm hadron mass distributions for 2015 data. $D^0 \rightarrow K^- \pi^+$ candidates were only collected during July 2015. The (red) solid shape shows the background component of the fit.

Figure 6: Charm hadron mass distributions for Run 1 and 2015 data. The (red) solid shape shows the background component of the fit.
A The dimuon mass distribution by year and polarity

This appendix shows dimuon mass distributions for data sub-samples. The datasets collected in 2011 and 2012 are shown separately in Fig. 7. Fig. 8 further splits the data samples for each year by magnet polarity. The amount of minimum bias data varied considerably over different data-taking periods, as can be seen comparing for instance Figs. 8c and 8d for 2012 data. Fig. 9 shows zooms into the 3–200 GeV/c² range.

Fig. 10 shows a selection of dimuon mass distributions without any offline particle identification (PID) requirements applied on dimuons selection by the inclusive stripping line. For the dimuons obtained from minimum bias triggers, the set of loose PID cuts are applied. There are $4.5 \times 10^9$ dimuons in Fig. 10c.

Figure 7: Dimuon mass distribution divided by trigger groups (see text) for Run 1 data. An inset plot with a zoom on the bottomonium region is shown on the top right corner.
Figure 8: Dimuon mass distribution divided by trigger groups (see text) split by magnet polarity. An inset plot with a zoom on the bottomonium region is shown on the top right corner.
Figure 9: Dimuon mass distribution in 3–200 GeV/c^2 range.
Figure 10: Dimuon mass distribution divided by trigger groups (see text) with no additional PID cuts applied. An inset plot with a zoom on the bottomonium region is shown on the top right corner.
Figure 11: Charm hadron mass distributions for 2011 DOWN data. The (red) solid shape shows the background component of the fit.

B Charm hadron mass distributions by year and polarity

Figs. 11-16 show charm hadron mass distributions for various subsets of Run 1 data. Figs. 17-18 show those of 2015. Note that only $D^0$ candidates associated to a $D^*$ were saved in 2015, except during July where individual $D^0$ candidates were also saved.

The yields are summarised in Table 1. The effect of the new trigger scheme is most visible in $D^+$ and $D_s^+$ distributions. While 11 million $D_s^+$ mesons per fb$^{-1}$ were collected in Run 1, this number increased to almost 100 million in Run 2. A factor two can be accounted to the increase in proton-proton collision centre-of-mass energy [28], the rest is due to improvements in the trigger and lower thresholds applied in the hardware trigger. The latter may not persist at larger instantaneous luminosity and this increase may not fully persist throughout of Run 2.
Figure 12: Charm hadron mass distributions for 2011 UP data. The (red) solid shape shows the background component of the fit.

Figure 13: Charm hadron mass distributions for 2011 data. The (red) solid shape shows the background component of the fit.
Figure 14: Charm hadron mass distributions for 2012 DOWN data. The (red) solid shape shows the background component of the fit.

Figure 15: Charm hadron mass distributions for 2012 UP data. The (red) solid shape shows the background component of the fit.
Figure 16: Charm hadron mass distributions for 2012 data. The (red) solid shape shows the background component of the fit.

Table 1: Fitted yields in million per channel and dataset. “All 2015” also contains the July sample.

<table>
<thead>
<tr>
<th>Data</th>
<th>$\int L , dt$ [fb$^{-1}$]</th>
<th>$K^-\pi^+$</th>
<th>$K^-K^+$</th>
<th>$D^+$</th>
<th>$D_0^+$</th>
<th>$D^*$</th>
<th>$A_c^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 DOWN</td>
<td>0.6</td>
<td>109</td>
<td>13</td>
<td>60</td>
<td>6</td>
<td>23</td>
<td>2</td>
</tr>
<tr>
<td>2011 UP</td>
<td>0.4</td>
<td>76</td>
<td>9</td>
<td>42</td>
<td>4</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>2011</td>
<td>1.0</td>
<td>185</td>
<td>21</td>
<td>102</td>
<td>10</td>
<td>38</td>
<td>3</td>
</tr>
<tr>
<td>2012 DOWN</td>
<td>1.0</td>
<td>226</td>
<td>26</td>
<td>154</td>
<td>12</td>
<td>47</td>
<td>4</td>
</tr>
<tr>
<td>2012 UP</td>
<td>1.0</td>
<td>219</td>
<td>25</td>
<td>149</td>
<td>12</td>
<td>46</td>
<td>4</td>
</tr>
<tr>
<td>2012</td>
<td>2.0</td>
<td>445</td>
<td>51</td>
<td>302</td>
<td>25</td>
<td>92</td>
<td>9</td>
</tr>
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<td>Run 1</td>
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<td>630</td>
<td>73</td>
<td>404</td>
<td>34</td>
<td>131</td>
<td>11</td>
</tr>
<tr>
<td>Aug–Nov 2015 DOWN</td>
<td>0.2</td>
<td>114</td>
<td>18</td>
<td>33</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug–Nov 2015 UP</td>
<td>0.1</td>
<td>74</td>
<td>12</td>
<td>22</td>
<td>3</td>
<td></td>
<td></td>
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<tr>
<td>All 2015</td>
<td>0.3</td>
<td>3</td>
<td>191</td>
<td>29</td>
<td>55</td>
<td>8</td>
<td></td>
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<tr>
<td>Run 1+2015</td>
<td>3.3</td>
<td>633</td>
<td>73</td>
<td>595</td>
<td>64</td>
<td>186</td>
<td>19</td>
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Figure 17: Charm hadron mass distributions for Aug–Nov 2015 DOWN data. The (red) solid shape shows the background component of the fit.
Figure 18: Charm hadron mass distributions for Aug–Nov 2015 UP data. The (red) solid shape shows the background component of the fit.
References


