Muon signatures in ATLAS: A search for new physics in ±± events
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Chapter 4
Muons from pion and kaon decays

In the previous chapter we introduced a template fitting method able to estimate the muon momentum scale and resolution in early collision data. Apart from determining the momentum scale and resolution of muons in a certain data sample, this method also automatically estimates the fraction of muons produced in the decay of either a pion or kaon. As muons from $\pi/K$-decays form a background for most analyses based on prompt muons, determining this fraction is an important measurement in its own right.

In this chapter we describe a template fitting method, similar to the one from Chapter 3, able to estimate the fraction of muons from pion and kaon decays in a general muon sample. We then apply this method to quantify the contribution of pions and kaons to the invariant mass distribution of muon pairs in ATLAS [39,40]. Understanding this distribution is an important step in understanding the background of any multi-muon analysis, including the same-sign prompt muon cross-section measurement presented in Chapter 6.

4.1 Introduction

The total cross-section of proton-proton interactions at the LHC is dominated by multi-jet events. As jets often include a number of pions and kaons, the total production of light mesons at the LHC is multiple orders of magnitude higher than that of prompt muons. Because both pions and kaons can decay to muons, with a branching ratio of 100% and 63.6% respectively, this results in a large number of muons from $\pi/K$ decays.

As shown in Chapter 3, the combined pion and kaon contribution to muon samples can be estimated by fitting the $\Delta p_T$ distribution\(^1\) of the combined muons using templates to describe the separate $\pi/K$ and non-$\pi/K$ distributions. Performing this analysis on inclusive single muon samples results in plots such as the ones shown in Figure 4.1 [39] which show the estimated non-$\pi/K$ fraction in these samples as a function of muon $p_T$. At low momentum more than half the reconstructed muons originate from either a pion or a kaon. This relative contribution decreases rapidly with increasing momentum.

In this chapter we study the $\pi/K$ contribution to the invariant mass distribution of muon pairs in ATLAS. Figure 4.2 shows this distribution for opposite-sign combined muon

\(^1\)The definition of the momentum imbalance is given in Equation 3.1
Figure 4.1: The estimated non-$\pi/K$ fraction as a function of muon $p_T$ in an inclusive single muon sample for two different $\eta$ regions, compared to the fraction in a simulated Minimum Bias sample. The results are obtained using a template fitting method on the $\Delta p/p$ distribution of the muons [39].

pairs with at least one muon with $p_T > 4$ GeV and the other $p_T > 3$ GeV. This selection is chosen because it is close to the minimum $p_T$ requirement for combined muons and therefore optimal for the study of low mass resonances, which are greatly reduced by stronger $p_T$ requirements on the muons. The invariant mass distribution of Figure 4.2 shows clear peaks at mass values corresponding to particles that can decay to two muons, on top of a smooth continuum distribution. The resonances can be used to calculate the cross-section and decay time of the parent particles.

The smooth distribution underneath these resonances consists mainly of events with two muons produced in two independent decay chains, such as in $b\bar{b}$- or $c\bar{c}$-events with one muon produced in the decay of the quark and the other in the decay of the anti-quark. Another contribution comes from events where the muon pair was produced as part of a three or more body decay of a single particle, such as one muon produced in the direct decay of a $b$- or $c$-quark and the other produced in the subsequent decay of the same particle. In both of these cases the dominant contribution consists of muons produced in the direct decay of a $b$- or $c$-quarks, but, due to the large cross-section of low momentum muons from pions and kaons, there is also a significant contribution of events where at least one of the muons was produced in a $\pi/K$ decay. At invariant masses much larger than the $b\bar{b}$ invariant mass the spectrum of Figure 4.2 also contains a significant contribution of muon pairs produced in Drell-Yan processes.

We estimate the $\pi/K$ fraction of muon samples using a template fitting method similar to the one described in Chapter 3. The differences between both methods, discussed in Section 4.2, are aimed at stabilising the fitted fraction and improving the accuracy of the
4.2. The $\pi/K$ fraction in single muon samples

One possible way to estimate the $\pi/K$ fraction of muon samples is to use the template fitting method described in Chapter 3, which fits the $\pi/K$ and non-$\pi/K$ contributions to the $\Delta p/p$ distribution of combined muons. Although this method is able to reliably estimate the $\pi/K$ fraction of muon samples, it leads to relatively large systematic uncertainties as the fit is not always able to correctly separate the Landau and Gaussian component of the signal distribution (Equation 3.2). This affects the tail of the fitted signal distribution, thereby changing the estimated $\pi/K$ fraction.

To avoid this uncertainty we use a slightly modified method to estimate the $\pi/K$ fraction specifically for low momentum muons. The most notable difference is the use of a second discriminant, called the scattering significance, to help separate $\pi/K$ decays from other muons.

A statistical method is used to calculate the $\pi/K$ contribution to muon pair samples. This method, explained in Section 4.3, is first validated on simulated muon pairs (Section 4.4) and then applied on the data set used to obtain Figure 4.2 (Section 4.5). The results, in terms of the estimated $\pi/K$ contribution to the opposite-sign and same-sign invariant mass distribution of muon pairs in ATLAS, are presented in Section 4.6.

Figure 4.2: The invariant mass distribution of opposite-sign muon pairs in ATLAS. The event selection is given in Section 4.5 [40].
fraction of muon samples, in which both the templates for muons from pion and kaon decays and other muons are constructed from simulated events. Furthermore we use a second discriminant, called the scattering significance, to increase the discriminating power of the template method.

4.2.1 Discriminants

As discussed in Chapter 3, the long life-time of pions and kaons ensures that the majority of decays occur within or behind the Inner Detector volume. Such late decays in flight result in measured tracks which are partially formed by the meson before decaying and partially by the produced muon, with a discontinuity in both momentum and propagation direction at the decay point due to the emission of a neutrino. Since the tracking algorithms used in ATLAS assume that each track corresponds to one particle, these meson/muon tracks are reconstructed as one track with properties that are some combination of the two real particles. If the angle between the muon and meson trajectory or the momentum difference between both particles is large, the reconstructed track is typically of poor quality (large $\chi^2$) and the track is rejected by the tracking algorithms. In most pion and kaon decays however this emission angle is small and the track is reconstructed as a combined muon.

Based on this information we define two discriminating variables sensitive to discontinuities in the reconstructed muon tracks: The momentum imbalance, $\Delta p$, which describes the relative momentum difference between the Inner Detector (ID) and Muon Spectrometer (MS) track and the scattering significance, which describes the probability of a momentum discontinuity within the ID track. The template method used in this chapter is based on a composite discriminant consisting of a linear sum of these two variables. The momentum imbalance, scattering significance and composite discriminant are described separately.

Momentum imbalance

The momentum imbalance, $\Delta p$, of combined muons is already introduced in Section 3.2 including a discussion on the difference in $\Delta p$ distribution between muons from $\pi/K$ decays and all other muons. We shall therefore not repeat this discussion here, but focus on the differences between the templates used in Chapter 3 and those used in this chapter.

In this chapter we describe the $\Delta p$ distribution of both categories of muons by templates built from simulated events, instead of using the Landau-Gauss convolution of Equation 3.2 for the non-$\pi/K$ distribution. As both template shapes are affected by the muon momentum scale and resolution, which is different in data and simulation, we modify them by allowing a combined shift of the two templates along the $\Delta p$-axis and by performing a convolution of both templates with a Gaussian. The motivation for this is given in Section 3.2.2. Although both the width of the Gaussian and the shift value could be calculated from the difference in scale and resolution obtained in Chapter 3, both variables are left as free parameters. This does not affect the stability of the fit and removes any possible systematic uncertainty due to the uncertainty on the fitted scale and resolution.
4.2. The $\pi/K$ fraction in single muon samples

Scattering significance

The scattering significance is a measure for the likelihood of a discontinuity in momentum along an ID track. It is measured by fully refitting the track, allowing it to scatter at 8 to 16 distinct positions along its trajectory and then comparing these results with the expected angles due to multiple scattering, determined by the material thickness between the scattering positions. As the analysis performed in this chapter is limited to muons with $|\eta| < 1.05$, for which the TRT detector provides no $\eta$ information, only scattering along the $\phi$-coordinate is used to determine the scattering significance.

This refitting procedure is illustrated in Figure 4.3 which shows schematically the decay of $\pi/K$ track to a muon track within the ID volume. The left figure indicates the original fitted track while the right figure shows the refitted track which scatters at specified scattering positions.

![Figure 4.3: A schematic illustration of a $\pi/K$ track decaying to a muon track within the ID volume with the originally fitted ID track (left) and the refitted track used to calculate the scattering significance (right). The scattering positions are indicated as well as $\Delta \phi_i$ for position 2. The dashed lines in the right image indicate the extrapolation of the fit between positions $i-1$ and $i$ past position $i$. The angle $\Delta \phi_i$ corresponds to the angle between this extrapolation and the actual fit (the red line) at point $i$. For scattering positions before the decay point the refitted track is scattered outwards and $\Delta \phi_i > 0$ while after the decay point the scattering is inwards and $\Delta \phi_i < 0$.](image)

We define the signed residual of a track at scatter position $i$ as:

$$s_i \equiv q \frac{\Delta \phi_i}{\phi_{i}^{\text{HISC}}},$$

where $q$ denotes the charge of the track, $\Delta \phi_i$ the fitted scattering angle, obtained by the refit, at position $i$ and $\phi_{i}^{\text{HISC}}$ the expected scattering angle due to multiple scattering. A non-zero scattering angle corresponds to a change in curvature and therefore momentum.

For $\pi/K$ decays within the ID volume the fitted curvature will generally correspond to a higher momentum before the decay point and a lower momentum after. Therefore $s_i$
will typically be positive for positions \( i \) before the decay point and negative after. This can be seen in Figure 4.3 where \( \Delta \phi \) and therefore \( s_i \) is positive for scattering positions 2, 3 and 4, before the decay point, and negative for position 5 and 6.

Using this information we define the position scattering significance of a track at position \( k \) as:

\[
S_P(k) \equiv \frac{1}{\sqrt{n}} \left( \sum_{i=1}^{k} s_i - \sum_{j=k+1}^{n} s_j \right),
\]

(4.2)

where \( n \) denotes the total number of scattering layers along the track. Due to the discontinuity in momentum, \( S_P(k) \) should be non-zero for scattering positions close to a possible decay point. The scattering significance, \( S \), of the ID track is defined as the maximum \( S_P(k) \) along the track trajectory:

\[
S \equiv \text{Max}\{S_P(k)\}.
\]

(4.3)

### Composite discriminant

Both the momentum imbalance and the scattering significance of combined muon tracks can be used to differentiate between muons from \( \pi/K \) decays and other muons. The momentum imbalance is particularly useful for high momentum tracks where the momentum difference between the meson and muon is large and the measured ID tracks are typically dominated by the meson, leading to an ID momentum measurement close to the meson momentum. At low momentum the \( \Delta p \) distribution of muons from \( \pi/K \) decays is narrower, especially due to the requirement that the produced muon must have sufficient energy to traverse the calorimeters to produce a MS track. This effectively introduces a \( p_T > 3 \) GeV selection cut on the muon, which for low momentum mesons limits the maximum momentum difference between the meson and the muon and thereby the width of the \( \Delta p \) distribution. The scattering significance on the other hand is most powerful for low momentum tracks, where the decay angle between the meson and the muon is largest.

As both discriminants focus on different sets of muons we use a composite discriminant, \( c \), defined as a linear sum of the absolute value of the momentum imbalance and the scattering significance:

\[
c(r) \equiv \frac{\Delta p}{p} + r|S|, \quad \text{with } r = 0.07
\]

(4.4)

The composite discriminant distribution for muons from \( \pi/K \) decays and for all other muons in the JF17 simulated sample\(^2\) are shown in the left plot of Figure 4.4. The value of the coefficient \( r \) in Equation 4.4 is chosen such that is maximises the separation power of the composite discriminant. The separation is defined as:

\[
\text{separation } s(r) = \int_{-\infty}^{\infty} \frac{(f_{\text{other}}(c(r)) - f_{\pi/K}(c(r)))^2}{f_{\text{other}}(c(r)) + f_{\pi/K}(c(r))} \, dc
\]

(4.5)

where \( r \) denotes the coefficient and \( f_{\pi/K}(c(r)) \) and \( f_{\text{other}}(c(r)) \) are the composite discriminant distributions of muons from \( \pi/K \) decays and other muons respectively. The

\(^2\)The JF17 sample is described in Appendix A
4.2. The $\pi/K$ fraction in single muon samples

optimization curve obtained using the JF17 simulated sample is shown in the right plot of Figure 4.4.

![Figure 4.4: Left: The normalized $c(r=0.07)$ distribution for muons from $\pi/K$ decays (light green line) and other muons (dark blue line) in the JF17 simulated sample. Right: The separation of the composite discriminant on the JF17 simulated sample as a function of the coefficient $r$ [40].](image)

### 4.2.2 Fitting the $\pi/K$ fraction of muon samples

We estimate the $\pi/K$ fraction of muon samples by performing an unbinned likelihood fit on the composite discriminant distribution of these samples using templates to describe the $\pi/K$ and non-$\pi/K$ distributions. The fitted normalization of the templates is used to calculate the $\pi/K$ fraction.

The templates used in the fit are constructed from simulated muons in the JF17 sample in a similar way as the background templates in Chapter 3. The only difference is that we include a shift of the $\Delta p_T$ distribution as well as a convolution with a Gaussian to account for differences between data and simulation. Therefore each fit has three free parameters: the $\pi/K$ fraction, the shift value and the width of the Gaussian. The statistical uncertainty on the $\pi/K$ fraction is given by a profile likelihood fit.

As an example Figure 4.5 shows the composite discriminant distribution for single muons with $|\eta| < 1.05$ and $4 \text{ GeV} < p_T < 5 \text{ GeV}$ in data as well as the best fit and the fitted $\pi/K$ and non-$\pi/K$ components.

### 4.2.3 Systematic uncertainty determination

The evaluation of the systematic uncertainties associated with this analysis, is similar to the procedure used in Chapter 3. We consider three types of systematic uncertainties:
Figure 4.5: The composite discriminant distribution for single muons with $|\eta| < 1.05$ and 4 GeV < $p_T$ < 5 GeV in data (black dots). The best fit of this distribution is given by the black line. The light green and dark blue lines indicate the fitted $\pi/K$ and non-$\pi/K$ components respectively, obtained using different toy-MC-templates [40].

- Uncertainty due to limited simulated statistics: We estimate this uncertainty by performing fits using toy-MC-templates, as described in Section 3.2.3.

- Uncertainty due to possible differences in the pion to kaon ratio between collision data and simulated events: This is estimated by performing two additional fits: one with a $\pi/K$ template with twice the pion content and the other with twice the kaon content. (As described in Section 3.2.3.)

- Uncertainty due to the chosen fitting method: This uncertainty is estimated by performing fits using binned histograms instead of the constructed templates. These results are compared to the $\pi/K$ fraction obtained from template fits performed with unconvoluted and not shifted templates. The difference between both methods is at most 1%, we therefore add an uncertainty of 1% to all fit results due to this effect. The uncertainty on the fitting method was not considered in Chapter 3 because the results of that analysis are obtained from the properties of the signal template described by a function.

For fits performed on large data samples the uncertainty due to simulated statistics dominates. As this uncertainty is also present in the calculation of the other systematic uncertainties we can use the same argument as in Section 3.2.3 and only quote the largest uncertainty. However all fits performed in this chapter are done on small data samples (narrow invariant mass bins), where this is not the case. We therefore assume no correlation between the systematic uncertainties and add them in quadrature.
4.3 The π/K contribution in dimuon samples

In the previous section we have introduced a template fitting method based on the composite discriminant to estimate the π/K fraction of muon samples. In this section we describe the statistical procedure necessary to apply this method on muon pairs.

The method to estimate the π/K contribution to muon pairs used in this chapter is based on the fact that although the template shapes depend on the properties (pT and η) of the muon (and meson), they are independent on the topology of the rest of the event. This means that the composite discriminant distribution of muons is independent on the existence or the properties of a second muon.

Given this information we divide all muons in the considered dimuon sample into pT-η bins and fit the π/K fraction in each bin using the template fitting method described in Section 4.2. The probability of a muon in pT-η bin i to have been produced in a pion or kaon decay is denoted as ωi and is equal to the estimated π/K fraction in this bin.

Assuming no correlation between the results in different bins, an assumption which is tested by performing this analysis on simulated muon pairs (Section 4.4), the probability of a muon pair with one muon in bin i and the other in bin j to not contain a muon from either a pion or kaon decay is given by:

\[ \omega_{ij}^{(0)} = (1 - \omega_i)(1 - \omega_j). \]  

The probability that at least one of the muons is from a pion or kaon decay is therefore given by:

\[ \omega_{ij}^{(1+)} = 1 - (1 - \omega_i)(1 - \omega_j). \]  

Using these probabilities the total number of muons pairs without π/K decays, N(0), and with at least one muon from π/K decay, N(1+), is given by:

\[ N^{(0)} = \sum_{ij} \omega_{ij}^{(0)} n_{ij}, \quad \text{and} \quad N^{(1+)} = \sum_{ij} \omega_{ij}^{(1+)} n_{ij}, \]  

where \( n_{ij} \) is the total number of events with one muon in pT-η bin i and the other in j.

The uncertainties on \( \omega_{ij}^{(0)} \) and \( \omega_{ij}^{(1+)} \) are given by:

\[ \sigma(\omega_{ij}^{(0)})^2 = \sigma(\omega_{ij}^{(1+)})^2 = \sigma_{\omega_i}^2 (1 - \omega_j)^2 + \sigma_{\omega_j}^2 (1 - \omega_i)^2, \quad i \neq j \]  

where \( \omega_{\text{syst}} = \sqrt{\sigma_{\omega_i,\text{syst}}^2 + \sigma_{\omega_j,\text{stat}}^2} \) the combined statistical and systematic uncertainty of \( \omega_i \).

When both muons are in the same pT-η bin the estimated π/K fraction for both muons are automatically equal and therefore fully correlated. The uncertainty is then given by:

\[ \sigma(\omega_i^{(0)})^2 = \sigma(\omega_i^{(1+)})^2 = 4 \sigma_{\omega_i}^2 (1 - \omega_i)^2. \]  

The total uncertainty on \( N^{(0)} \) and \( N^{(1+)} \) are given by:

\[ \left( \sigma^{(0)} \right)^2 = \sum_{ij} (\omega_{ij}^{(0)} n_{ij} + n_{ij}^2 \sigma(\omega_{ij}^{(0)})^2), \]
\[
\left( \sigma^{(1+)} \right)^2 = \sum_{ij} (\omega_{ij}^{(1+)} n_{ij} + n_{ij}^2 \sigma (\omega_{ij}^{(1+)}))^2,
\]

where the first term corresponds to the Poisson uncertainty on the observed number of events and the second term is the propagation of the uncertainty related to the fits.

The \(\pi/K\) contribution to the invariant mass distribution of muon pairs

Equation 4.8, 4.11 and 4.12 give the best estimate and the uncertainty on the \(\pi/K\) contribution to muon pairs. By calculating these values for narrow invariant mass bins it is possible to construct the \(\pi/K\) contribution to the invariant mass distribution of same-sign and opposite-sign muon pairs in ATLAS. The results of this procedure are shown in Section 4.6.

In this chapter we only consider muons within the MS barrel region \(|\eta| < 1.05\) where the track quality and therefore the template shapes are relatively well understood. As the template dependence on \(\eta\) in this region is negligible, no binning in \(\eta\) is used.

A fine binning in invariant mass is necessary to observe and study narrow resonances, however it introduces some additional uncertainties. The limited number of events per bin means that most bins have insufficient statistics to perform the full fitting procedure of Section 4.2 without risking unstable fit results. Therefore instead of leaving the shift and the convolution of the \(\Delta p\) distribution as free parameters we generally use a common value depending on the \(p_T\) bin obtained by fitting single muon data samples. Only in bins with more than 500 entries the full fitting method is used. In practise these are only bins in the center of the \(J/\psi\) peak.

Using a common value for the shift and convolution of the \(\Delta p\) distribution independent of the invariant mass bin is based on the idea that the energy-loss of muons is independent on the properties of the second muon and therefore on the true invariant mass of both particles. Unfortunately some dependence on the invariant mass does exist since both the measured invariant mass and the composite discriminant depend on the muon track quality. This introduces an addition systematic uncertainty on the estimated \(\pi/K\) fraction.

To illustrate this, take muon pairs produced in the decay of a \(J/\psi\) particle. As the width of the resonance depends strongly on the resolution of the tracks, the track quality of muon pairs with a reconstructed invariant mass in the center of the resonance is generally better than that of muon pairs which are a few sigma away from the central value. Therefore the composite discriminant distribution for \(J/\psi\) decays in the center of the resonance is narrower than in the side-bands.

Without compensating for this effect in the template shapes the amount of muon pairs with at least one muon from a pion or kaon decay will be slightly underestimated in the center of resonances and overestimated on the sides. As the amount of over-/underestimation of the events in bin \(m_{\mu\mu}\) depends on the number of events in the surrounding bin, at first order this uncertainty is given by the gradient of the number of events in the considered bin. We therefore take the following relative difference in events as the systematic uncertainty due to the uncertainty on the measured invariant mass and
add it to quadrature to the other fit uncertainties.

\[ \frac{\Delta n}{n} \equiv \frac{n(m'_{\mu\mu}) - n(m_{\mu\mu})}{n(m_{\mu\mu})} \]  

(4.13)

where \( n(m_{\mu\mu}) \) denotes the number of events (per mass unit) at mass \( m_{\mu\mu} \). Two values of \( m'_{\mu\mu} \) are used chosen to represent an overestimation and underestimation of the measured invariant mass by 0.5%.

### 4.4 Validation

The method described in Section 4.2 and 4.3 is validated on simulated opposite-sign muon pairs in a merged sample of 10 million simulated \( b\bar{b} \) and 10 million \( c\bar{c} \) events. This sample, denoted as \( b\bar{b}/c\bar{c} \rightarrow \mu^{+}X \) is described in more detail in Appendix A. The result of this validation is shown in the left plot of Figure 4.6 which shows the invariant mass distribution (black line/dots) of all muon pairs in the samples as well as the distribution for pairs with zero (dark blue line) and at least one muon from pion or kaon decays (light green line). The estimated distributions for the pairs with and without at least one muon from \( \pi/K \) decays are shown by the light green squares and dark blue triangles respectively. The compatibility between the true and estimated distribution is excellent. This is further illustrated in the right plot of Figure 4.6 which shows the ratio of estimated number of events without muons from \( \pi/K \) decays over the true value, as a function of the invariant mass. The discrepancy at very low invariant mass is mostly due to the fact that these mass-bins are dominated by very low momentum muon tracks where the discriminants are known to be less reliable. The agreement between the true and fitted value for the rest of the distribution proves the validity of this method.

### 4.5 Data set and event selection

The results shown in this chapter are obtained from data collected by the ATLAS experiment between the 30th of March and the 30th of August 2010\(^3\), passing data-quality cuts and triggered using an event filter trigger for muons with a transverse momentum above 4 GeV (EF\(_{\mu4}\))\(^4\). For part of the considered period this trigger was prescaled, resulting in 1.5 pb\(^{-1}\) of data collected out of 3.4 pb\(^{-1}\) delivered integrated luminosity.

The offline event selection requires events with at least three ID tracks associated to the primary vertex and at least one muon pair with the following characteristics:

- Both muons are in the MS barrel region: \(|\eta| < 1.05\)
- One muon with \( p_T > 4 \) GeV, the other with \( p_T > 3 \) GeV
- The ID track of both muons has at least 1 hit in the pixel and 6 hits in the SCT detector

\(^3\)This corresponds to Period A to F of 2010 (see Table 2.1).
\(^4\)The EF\(_{\mu4}\) trigger is described in Section 2.4.2
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4.6 Results

Applying the template fitting method described in this chapter on the data sample introduced in Section 4.5 results in the invariant mass distributions of Figure 4.7, where the top plot shows the distribution for opposite-sign muon pairs, and the bottom plot its same-sign equivalent. For both distributions the estimated distribution of pairs with and without at least one muon from a pion or kaon decay is shown as well.

The total fraction of pairs with at least one muon from $\pi/K$ decays is estimated to be $68 \pm 2\%$ for same-sign and $31 \pm 4\%$ for opposite-sign pairs. The fraction of dimuons where both muons were produced in the decay of a pion or kaon is not shown in Figure 4.7. The total estimated fraction is $22 \pm 2\%$ for same-sign and $5 \pm 1\%$ for opposite-sign pairs.

It can be seen from Figure 4.7 that the $\pi/K$ contribution produces a smooth background in the invariant mass distributions and that all resonances are clearly produced.
Figure 4.7: The invariant mass distribution of opposite-sign (top) and same-sign (bottom) dimuon pairs in data (black dots) and the fitted contribution for muons pair with (light green squares) and without (dark blue triangles) at least one muon from $\pi/K$ decays [40].
by two non-$\pi/K$ muons. The difference in fraction of events with at least one muon from $\pi/K$ decays between the same-sign and opposite-sign muon pairs is mostly due to the higher cross-section for opposite-sign pairs from prompt muons and muons from the decay of heavy flavour quarks. This can be seen in Figure 4.8 where we plot the difference in distribution between the opposite-sign and same-sign muon pairs for three different mass ranges. The background from $\pi/K$ decays is the same for the same-sign and opposite-sign muon pairs over most of the invariant mass range, as this background is caused by combining a muon from $\pi/K$ decays to an unrelated other muon in the event. At very low mass ranges this is no longer the case and more opposite-sign pairs with at least 1 muon from $\pi/K$ decays were estimated than same-sign pairs. This difference is dominated by decays of charmed and beauty mesons to a lepton and at least one pion or kaon, such as: $D^0 \rightarrow K^{\pm} \mu^{\mp} \nu$.

4.7 Conclusion

Muons from pion and kaon decays form a background for any analysis involving prompt muons. In this chapter we introduced a template fitting method to estimate the $\pi/K$ fraction of muon samples in a data driven fashion. This template method is based on the difference in both the momentum imbalance and the scattering significance of muon tracks from $\pi/K$ decays and other sources. By using a statistical method we can estimate the $\pi/K$ contribution to dimuon samples and therefore determine the $\pi/K$ contribution to the invariant mass distribution of muon pairs in ATLAS. This analysis was validated on simulated $b\bar{b}$ and $c\bar{c}$ events, resulting in excellent agreement between the true and estimated composition of the distributions.

The estimated $\pi/K$ contribution to the invariant mass distributions in data is shown in Figure 4.7. Apart form the very low mass region ($m_{\mu\mu} < 2$ GeV), the estimated $\pi/K$ contributions to the opposite- and same-sign invariant mass distributions are equal within statistical errors. Specifically, the smooth distribution for the invariant mass distribution of muon pairs with at least one $\pi/K$ decay shows no contribution to any of the dimuon resonances. This is not unexpected since, apart from the low mass region, the $\pi/K$ contribution is dominated by events where a muon from a pion or kaon decay is paired with an independently produced second muon.

In total $68 \pm 2\%$ of the selected same-sign and $31 \pm 4\%$ of the opposite-sign muon pairs contain at least one muon from $\pi/K$ decays. These numbers illustrate the importance of considering and quantifying the contribution from muons from pion and kaon decays in any multi-muon analysis in ATLAS.
Figure 4.8: The difference in invariant mass distribution between opposite-sign and same-sign dimuon pairs in data (black dots) and the fitted difference for muon pairs with (light green squares) and without (dark blue triangles) at least one muon from π/K decays, for different mass ranges [40].