Fermi-Dirac correlations
in $Z \rightarrow \bar{p}pX$ events

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Abstract
The correlations between antiproton-antiproton and proton-proton pairs, observed in the DELPHI experiment at LEP, are studied as a function of the four-momentum difference. The analysis makes use of the particle identification capabilities of the DELPHI detector. The correlation function, determined on the basis of three different reference samples, exhibits a strong depletion in the region of the four-momentum difference of the pair $Q < 2$ GeV, which we interpret as the effect being due to Fermi-Dirac statistics. Assuming a Gaussian parametrisation, the fit to the correlation function yields the source radius $R = 0.16 \pm 0.04$ (stat) $\pm 0.03$ (syst) fm and the correlation strength $\lambda = 0.67^{+0.19}_{-0.17}$ (stat) $\pm 0.18$ (syst).

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1 Introduction

The application of two-boson correlations to the measurement of the space-time volume of the hadron emission region can be extended to the study of identical fermion pairs. Instead of symmetrisation of the two-particle wave function, which is considered in the analyses of the Bose-Einstein correlation effect, the examination of the correlation radius can be based on the antisymmetrisation, which occurs for two identical fermions. In this case identical fermions cannot occupy the same quantum state owing to the Pauli exclusion principle. The exclusion causes a depletion in the probability distribution of the production of identical fermions close in space-time. This phenomenon is called the Fermi-Dirac correlation effect. The range of the above-mentioned depletion provides information about the space-time properties of hadronic sources. The quantum interference is usually studied employing the variable defined as the difference between the four-momenta of the two indistinguishable particles:

\[ Q = \sqrt{-\left( p_1^\alpha - p_2^\beta \right)^2}. \]

(1)

Using measured \( Q \) distributions it is feasible to construct the correlation function and estimate the correlation radius. The correlation function for two-particle correlations can be defined as follows:

\[ C_2(Q) = \frac{\rho_2(Q)}{\rho_2(Q)^{\text{REF}}}, \]

(2)

where \( \rho_2(Q) \) is the inclusive density distribution of two particles with the four-momenta difference \( Q \). The denominator in equation (2) is usually referred to as the reference density. It is a two-particle density distribution which approximately reflects the distribution without the Fermi-Dirac effect. However, the reference distribution should involve all possible correlations, except for the Fermi-Dirac ones, for example those in the distribution in the numerator which arise e.g. from the charge, energy-momentum or baryon number conservation, particle decays, and event topology.

This paper focuses on the Fermi-Dirac correlations of two antiprotons\(^1\) which were investigated using hadronic \( Z \) events recorded in the DELPHI experiment at LEP. Previous studies of the Bose-Einstein and Fermi-Dirac correlations for charged pions \([1]\), kaons \([2]\) and particularly for \( \Lambda \) particles \([3, 4]\) suggest a dependence of the correlation radius on hadronic mass. Recently, the ALEPH and OPAL experiments have published the results for \( \bar{p}p \) \([5, 6]\), supporting the evidence for the \( R(m) \) dependence.

2 Method of analysis

The crucial problem in Bose-Einstein or Fermi-Dirac correlation analyses is the definition of the reference sample. The simplest reference sample applied in many studies of Bose-Einstein and Fermi-Dirac correlations of identical charged particle pairs (like-sign) is the so-called “unlike” distribution: the distribution of oppositely charged particle pairs ( unlike-sign). A reference sample of this type might prove unsuitable for protons owing to the occurrence of strong correlations caused by the local baryon number conservation for \( p \bar{p} \) pairs.

\(^1\)Unless specifically stated, charge-conjugate particles are always implied.
Another method of constructing the reference sample is based on the choice of two identical fermions, each originating from a different event. The so-called “event-mixing” reference sample obtained in this way clearly does not exhibit the Fermi-Dirac effect. The major difficulty related to this kind of construction lies in the fact that not only the Fermi-Dirac effect is removed from the data sample but also all other kinds of correlations, for instance those resulting from the four-momentum conservation.

The third technique of constructing the reference sample employs the Monte Carlo (MC) simulated distribution without the Fermi-Dirac effect. The frequently used MC generators, like JETSET [7] based on the Lund string model, do not involve the Fermi-Dirac correlations. This procedure is acceptable provided there is an acceptably good data-MC agreement in basic distributions.

When the reference distribution is derived from the data (the unlike and event-mixed distributions), the so-called “double ratio” is generally used to correct the imperfections in the reference distribution:

\[
\mathcal{R}(Q) = \frac{\rho_2(Q)^{\text{data}}}{\rho_2(Q)^{\text{ref, data}}} \left/ \frac{\rho_2(Q)^{MC}}{\rho_2(Q)^{\text{ref, MC}}} \right.,
\]

where \(\rho_2(Q)^{\text{data}}\), \(\rho_2(Q)^{MC}\) indicate the Q distributions for the data and MC respectively, \(\rho_2(Q)^{\text{ref, data}}\), \(\rho_2(Q)^{\text{ref, MC}}\) denote the unlike or event-mixed Q distributions for the data and MC, correspondingly.

The parametrisation of the correlation function in formula (2), frequently used in experimental analyses with bosons, is the GGLP parametrisation [8]:

\[
C^B_2(Q) = N(1 + \lambda e^{-R^2Q^2}).
\]

The above formula is obtained on the assumption that the source is described by a spherically symmetric Gaussian density distribution of emitting centres. \(R\) in formula (4) (in GeV\(^{-1}\)) denotes the radius of the sphere describing the source shape, \(N\) accounts for imperfect normalisation of the correlation function, and the parameter \(\lambda\), introduced to describe partial incoherence of the source is called the chaocity parameter, with \(\lambda = 0\) in the case of a completely coherent source, and \(\lambda = 1\) when the source is entirely chaotic. In practice, numerous experimental effects influence the measured value of \(\lambda\).

For identical fermions, the antisymmetrisation requirement for the total wave function leads to an analogous parametrisation of their correlation function:

\[
C^I_2(Q) = N(1 - \lambda e^{-R^2Q^2}).
\]

Thus defined, the \(\lambda\) parameter includes both the information about incoherence of the source and the spin composition of the pair for \(Q \to 0\). According to [9], the maximum value of \(\lambda\) for entirely chaotic sources is 0.5.

3 Data selection and simulation

The analysis is based on the data recorded in the DELPHI detector at LEP at the centre-of-mass energy corresponding to the Z mass. A detailed description of the DELPHI detector and of its performance can be found in [10] and [11]. The principal source of particle identification information is the Ring Imaging Cherenkov (RICH). The sample of
2 million hadronic events recorded between 1994 and 1995, the period of the best quality RICH information, was used. Track and momentum measurements in the Silicon Micro-Vertex Detector (VD), the Inner Detector (ID), the Time Projection Chamber (TPC) and the Outer Detector (OD), all operating in a 1.2 T magnetic field, facilitated the charged-particle tracking and momentum determination.

The selection criteria for charged particles included the following requirements: the charged particle track length above 30 cm, at least one point of the trajectory measured in the VD, the track impact parameter with respect to the interaction point below 0.1 cm in the plane perpendicular to the beam direction (z) and the corresponding impact parameter along the beam direction below 1 cm, the track polar angle \( \theta \) between 25° and 155°. In addition, the requirement for the minimal particle momentum of 0.7 GeV was imposed. In the case of the proton sample the above cut determines the momentum region where the MC agrees very well with data.

Hadronic \( Z \) events were selected when the following conditions were satisfied: at least five charged particles and the total energy of all charged particles above \( 0.12 \sqrt{s} \), where \( \sqrt{s} \) denotes the center-of-mass energy. At least two protons (antiprotons) were required for the hadronic event to be accepted. Moreover, the protons were not allowed to be the decay products of an identified \( \Lambda \) hyperon. The proton candidates were selected using the particle identification information from the MACRIB package [12], which uses a neural network approach to combine all available identification measurements in the DELPHI detector. The proton identification variable XPRNET had to be greater than 0.7 in order to preselect the proton candidate sample. In the subsequent analysis this cut was altered within the range 0.90 – 0.97 such that samples with different purities could be studied. Another identification package RPROC0 [13] was also applied to compare the identification results. This package provided less efficient proton identification at the same purity as compared to MACRIB. It was finally used to check for possible biases in the analysis resulting from particle identification.

Using the above cuts a sample of about 180 thousand events with at least two proton candidates was preselected. A sample of higher purity requiring exactly two protons (antiproton) candidates having XPRNET> 0.95 in the event was used for the final analysis. The single proton purity for this sample is 85% (the purity is defined as a fraction of genuine protons coming the primary vertex) at an efficiency of 70%, as determined by the MC simulation. The purities for the \( \bar{p}p \) and \( pp \) samples were found to be 70% and 50% respectively, the latter being smaller due to the presence of protons in the material of the detector.

On the basis of the MC simulation it was found that the background contaminates strongly the low-\( Q \) region for the \( pp \) sample due to secondary interactions. For that reason the interference measurement in this sample demands a background subtraction. Therefore, the \( \bar{p}p \) sample is used in the standard analysis. The result for the \( pp \) sample is also quoted.

The analysis is performed for all jet topologies of the event. It has been ascertained that the results for the sample limited to two-jet events with the cut on thrust \( T > 0.95 \) agree within errors with the standard analysis.

The MC sample contains approximately 8 million hadronic events, generated using the JETSET 7.4 [7] model with parameters tuned as in [14], passed through the simulation program of the DELPHI detector DELSIM [11], and the same DELPHI reconstruction
program and analysis chain as for the data. About 560 thousand events with at least two proton candidates were preselected from this sample. Contrary to the Bose-Einstein analyses for $\pi^\pm\pi^\pm$ and $K^\pmK^\pm$, where the Bose-Einstein effect is simulated using the LUBOEI algorithm [15], the JETSET 7.4 program does not contain the Fermi-Dirac correlation effect. Thus the MC sample might be used as a reference sample in the Fermi-Dirac analysis.

4 Results

After the selection cuts, which were described in Sect.3, around 1000 $\bar{p}p$ pairs remained for the analysis in the data, compared to over 1000 expected from the JETSET MC. MC data are normalised to absolute luminosity. Detailed information about the number of $pp$, $\bar{p}p$ and $p\bar{p}$ pairs in data and MC samples (mixed samples for data and MC respectively) is included in Table 1.

Table 1: Number of $pp$, $\bar{p}p$ and $p\bar{p}$ pairs in data, MC and mixed samples for data and MC.

<table>
<thead>
<tr>
<th></th>
<th>DATA</th>
<th>MC</th>
<th>DATA-MIX</th>
<th>MC-MIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp$</td>
<td>1325</td>
<td>1268</td>
<td>4708</td>
<td>6833</td>
</tr>
<tr>
<td>$\bar{p}p$</td>
<td>955</td>
<td>893</td>
<td>3968</td>
<td>5219</td>
</tr>
<tr>
<td>$p\bar{p}$</td>
<td>6473</td>
<td>7004</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In the following, comparisons of one and two-particle distributions for the relevant variables are given, and the correlation functions based on various reference samples are constructed.

4.1 Data-MC comparison

The single-particle distributions of the momentum for protons and antiprotons in the data and MC are shown in Fig.1(left). A consistently good agreement between the data and MC (at the level of $10 - 15\%$) may be observed, in particular for momenta up to 10 GeV. The dip around 8 GeV is due to a smaller efficiency to tag protons in that momentum region.

The distributions of the cosine of opening angle $\theta$ in the thrust reference frame (see Sect. 4.2) for the like-sign ($pp$, $\bar{p}p$) and unlike-sign ($p\bar{p}$) pairs are compared to the MC predictions in Fig.1(right). Again, an acceptable agreement between the data and MC may be noticed.

In Fig.2 the $Q$ distributions in data are compared to the respective ones in the MC for the $pp$, $\bar{p}p$ and unlike-sign proton pairs. In the case of like-sign ($pp$, $\bar{p}p$) distributions the data points are below the MC prediction in the region of low-$Q$ values, while in the tails they agree well. In the $p\bar{p}$ distribution the MC underestimates the data for $p < 1$ GeV and overestimates the region $p \in (1 - 2)$ GeV. The total background, denoted by a dashed line, is superimposed in $pp$ and $\bar{p}p$ distributions, while the contribution from secondary interactions is represented by a filled histogram. It is clear that both the total background
and its secondary interaction part affect the $Q$ distribution for $pp$ more strongly than $\bar{p}\bar{p}$ pairs.

4.2 Mixed reference sample

The mixed reference sample is constructed using the following procedure. Momentum vectors of each $p$ ($\vec{p}$) of all accepted $pp$, $\bar{p}\bar{p}$ and $p\bar{p}$ pairs are stored in a buffer. For each momentum vector of $\vec{p}$ ($p$) from the $\bar{p}\bar{p}$ ($pp$) pair one momentum vector is uniformly drawn from the buffer, therefore for a given $\vec{p}_1\vec{p}_2$ ($p_1p_2$) event the two momentum-vector pairs ($\vec{p}_1\vec{p}_{mix,1}$, $\vec{p}_2\vec{p}_{mix,2}$) are derived. The above procedure is repeated for every $\vec{p}_1\vec{p}_2$ ($p_1p_2$) pair removing from the buffer the momenta already used.

There were two variants of the mixing procedure: with and without removing the already used momenta from the buffer. No significant change in the result was observed.

A comparison of the momentum distributions for the original and mixed samples, for $p$ and $\bar{p}$ separately, is shown in Fig.3(left). No distortions were found in the distributions resulting from the mixing. The cosine of the $\bar{p}\bar{p}$ ($pp$) opening angle $\theta$ distributions in the data and the mixed sample are shown in Fig.3(right). These distributions usually get distorted while mixing [3, 6]. No such distortions were observed in the present study.

The comparison of the $Q$ distributions in the data and in the mixed sample is shown Fig.4a,b. In the $Q < 2$ GeV region the overestimation of the data distributions by the mixed sample distributions is observed, particularly for the $\bar{p}\bar{p}$ pairs Fig.4b. The distributions for the mixed samples are very similar to the MC distributions in Fig.2a,b. Similarly, the $Q$ distributions for $\bar{p}\bar{p}$ and $pp$ obtained from MC mixed-events virtually coincide with the corresponding MC distributions.

4.3 Correlation function

Correlation functions are determined using three different reference samples: the MC, mixed-events and unlike pairs. Both the distributions, in the numerator and denominator in formula (2) have been normalised to 1. As has been mentioned above, the $Q$ distributions for $pp$, $\bar{p}\bar{p}$ obtained from the MC mixed-events coincide with the MC distributions. Therefore, the factor $(p_2(Q)^{MC}/p_2(Q)_{mix})$ in formula (3) is constant and thus it is unnecessary to resort to the double ratio (3) with the event-mixed reference sample to determine the correlation function.

The effect of the different definitions of the correlation function (with and without double ratio) was studied and subsequently included in the systematic errors. The double ratio definition of the correlation function was necessary only in the case of the unlike reference sample.

5 The correlation radius from $C_2(Q)$

The fits to the correlation function defined with respect to the event-mixing, MC and unlike reference samples for $\bar{p}\bar{p}$ pairs were performed applying the parametrisation given in formula (5). The alternative parametrisation, where the normalisation factor is fixed at 1, was also considered. The fitted range of the $Q$ variable was $0 < Q < 8.0$ GeV. The results of fits to the correlation function for $\bar{p}\bar{p}$ pairs are presented in Table 2. The entries
in brackets correspond to the fits where the normalisation factor in formula (5) remains free.

Table 2: Results of the fits to the correlation function $C_2(Q)$ for $\bar{p}p$ pairs using the parametrisation (5) where the normalisation factor is fixed at 1 and remains free (brackets), using the event-mixed, MC and unlike reference samples. The errors listed are only statistical.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Reference sample</th>
<th>Event-mixed</th>
<th>MC</th>
<th>Unlike</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R [\text{fm}]$</td>
<td>$0.16^{+0.04}_{-0.04}$</td>
<td>$0.17^{+0.04}_{-0.05}$</td>
<td>$0.20^{+0.04}_{-0.04}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$[0.15^{+0.05}_{-0.04}]$</td>
<td>$[0.16^{+0.04}_{-0.05}]$</td>
<td>$[0.20^{+0.04}_{-0.04}]$</td>
<td></td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$0.67^{+0.19}_{-0.17}$</td>
<td>$0.70^{+0.20}_{-0.17}$</td>
<td>$0.85^{+0.18}_{-0.16}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$[0.65^{+0.19}_{-0.16}]$</td>
<td>$[0.70^{+0.21}_{-0.17}]$</td>
<td>$[0.85^{+0.20}_{-0.18}]$</td>
<td></td>
</tr>
<tr>
<td>$N$</td>
<td>$1.03 \pm 0.05$</td>
<td>$1.00 \pm 0.05$</td>
<td>$0.96 \pm 0.05$</td>
<td></td>
</tr>
<tr>
<td>$\chi^2/ndf$</td>
<td>$18/23$</td>
<td>$24/23$</td>
<td>$25/23$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$[17/22]$</td>
<td>$[24/22]$</td>
<td>$[25/22]$</td>
<td></td>
</tr>
</tbody>
</table>

As may be observed in Table 2 all fits yield the normalisation factor in formula (5) compatible with 1. Therefore, the fit to the correlation function with parametrisation (5) assuming $N = 1$ has been chosen as the final result. The fits to the correlation function defined employing the MC, event-mixed as well as the unlike distributions, with parametrisation where the normalisation factor is fixed at 1, are shown in Fig.5 a,b,c, respectively. The analysis using the event mixing reference sample is based on the data itself and is to a lesser extent affected by assumptions, hence the final result is taken from the event mixing analysis (with the normalisation factor fixed at 1):

$$R = 0.16 \pm 0.04(\text{stat}) \text{ fm}$$

$$\lambda = 0.67^{+0.19}_{-0.17}(\text{stat}).$$

The methods based on the MC or unlike reference samples produce results which are consistent within errors with the event-mixing technique and are used only for a cross-check. The above numbers agree well with the results of the fit to the double ratio distribution, as defined with respect to the event-mixed reference sample, where the values of fitted parameters were as follows: $N = 1.05 \pm 0.06$, $R = 0.13^{+0.05}_{-0.04}$ fm, $\lambda = 0.63^{+0.19}_{-0.15}$ in the case of parametrisation where the normalisation factor remains free,
and $R = 0.16_{-0.04}^{+0.05}$ fm, $\lambda = 0.66_{-0.17}^{+0.21}$ when the normalisation factor is fixed at 1.

After subtracting the total background from the $Q$ distribution of $pp$ pairs, a fit to the correlation function with an event-mixed reference sample was also performed using parametrisation (5) with the normalisation factor being a free parameter. The obtained parameter values ($R = 0.19\pm0.07 (\text{stat})$ fm, $\lambda = 0.88\pm0.21 (\text{stat})$) agree well with those for $\bar{p}p$ pairs, however suffer from larger systematic error due to the background subtraction.

## 6 Systematic errors

We have studied systematic errors of the $R$ and $\lambda$ determination which could originate from the following sources: proton identification, double track resolution, background subtraction, different reference samples as well as the use of the double ratio, parametrisation of the correlation function, fit range and binning width in $Q$. With respect to the standard result: $R = (0.16 \pm 0.04)$ fm, $\lambda = 0.67_{-0.19}^{+0.19}$, the maximum variation of $R$ and $\lambda$ in a given test was taken as an estimate of the systematic error contribution. The total systematic error was obtained by summing in quadrature the individual contributions. The contributions to the systematic errors of $R$ and $\lambda$ are listed in Table 3. The system-

<table>
<thead>
<tr>
<th>systematic error source</th>
<th>$\Delta R$</th>
<th>$\Delta \lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>identification; XPRNET $\in (0.90 - 0.97)$</td>
<td>0.017</td>
<td>0.141</td>
</tr>
<tr>
<td>opening angle $\theta &gt; 2^{\circ}$</td>
<td>0.008</td>
<td>0.023</td>
</tr>
<tr>
<td>background subtraction</td>
<td>0.004</td>
<td>0.052</td>
</tr>
<tr>
<td>different reference samples</td>
<td>0.013</td>
<td>0.068</td>
</tr>
<tr>
<td>double ratio</td>
<td>0.002</td>
<td>0.011</td>
</tr>
<tr>
<td>$C_2(Q)$ parametrisation</td>
<td>0.011</td>
<td>0.022</td>
</tr>
<tr>
<td>fit range; $Q_{\text{MAX}} \in (6.0 - 9.0)$ GeV</td>
<td>0.003</td>
<td>0.005</td>
</tr>
<tr>
<td>$Q$-bin size; $\Delta Q \in (0.25 - 0.35)$ GeV</td>
<td>0.011</td>
<td>0.063</td>
</tr>
<tr>
<td>total systematic error</td>
<td>0.028</td>
<td>0.180</td>
</tr>
</tbody>
</table>

atic effects coming from proton identification were evaluated by studying $\bar{p}p$ samples with purities ranging from 60% to 90%. The effect of double track resolution was examined by selecting a sample with a two-track opening angle exceeding $2^{\circ}$. The effect of background subtraction was estimated by comparing the results of the fit to the correlation function in the case of background subtraction and with the background not being subtracted. The systematics due to the reference samples, the double ratio and the parametrisation of the correlation function were extracted from the results in Sect.5. The systematic error related to the choice of fit range was obtained by changing the upper limit of the $Q$ value from 6 to 9 GeV. The Coulomb repulsion between the particles in the pair were also examined by introducing a Gamov correction factor [16]. This had a negligible impact on the result, since it affects only the region of very low $Q$ values.

Having considered the above, the final result for the radius of the antiproton source is $R = 0.16\pm0.04 (\text{stat}) \pm 0.03 (\text{syst})$ fm and the incoherence parameter $\lambda = 0.67_{-0.17}^{+0.19} (\text{stat}) \pm 0.21 (\text{syst})$. The results of the fit to the correlation function for $R$ and $\lambda$ are listed in Table 4.
7 Summary and conclusions

We have studied the correlations in the four-momentum difference variable $Q$ for antiproton and proton pairs. Strong depletion in the correlation function is observed for $\bar{p}p$ and $pp$ in the region of $Q < 2$ GeV, contrary to the effect seen for $\bar{p}p$ pairs. These depletions can be an effect of the Pauli exclusion principle. The correlation function is fitted using the parametrisation (5) with the normalisation factor fixed at 1, which yields a very small Gaussian source radius and a large incoherence parameter:

$$R = 0.16 \pm 0.04(\text{stat}) \pm 0.03(\text{syst}) \text{ fm}$$

$$\lambda = 0.67^{+0.19}_{-0.17}(\text{stat}) \pm 0.18(\text{syst}).$$

The measurement based on the $pp$ sample, which is not as clean as the $\bar{p}p$ sample due to pollution from secondary interactions, yields a compatible result: $R = 0.19 \pm 0.07(\text{stat}) \pm 0.07(\text{syst}) \text{ fm}$, $\lambda = 0.88 \pm 0.21(\text{stat}) \pm 0.19(\text{syst})$.

All available experimental results point to a hadron source radius of $\sim (0.6 - 1.0)$ fm if measured by the Bose-Einstein interference of pions and kaons [1, 2] and a radius of $\sim (0.10 - 0.16)$ fm if measured by the Fermi-Dirac interference of $\Lambda$'s and protons [3, 4, 5, 6]. While the value of the radius for pions and kaons is well reconcilable with our present understanding of the hadronisation process, the value of the source dimension for protons and $\Lambda$ hyperons is not. For instance a radius of $O(0.10 \text{ fm})$ would imply an enormous energy density ($> 100 \text{ GeV/fm}^3$) of the source [9].

This small source radius is well explained in a model from A. Bialas and K. Zalewski [17] studying the dependence of the radius on the hadron masses. The model is based on the Björken-Gottfried relation which connects the space-time position of a hadron produced in the hadronisation process with its four-momentum. This relation is the consequence of fast expansion of the system. Such a four-momentum - space-time correlation leads to an apparent source size as observed in interferometry measurements, which is smaller than the real size. The model reproduces correctly the observed mass dependence of the source radius and the source elongation in $e^+e^-$ collisions [18].
References


Figure 1: (Left) Comparison of momentum distributions in the data (points) and MC (histogram) for (a) protons, (b) antiprotons. (Right) Distributions of the cosine of the angle between two-particle momentum-vectors calculated in the thrust reference frame: (a) like-sign $p\bar{p}$, (b) unlike-sign $p\bar{p}$ pairs. Points denote distributions for the data, histograms stand for the MC simulation.
Figure 2: $Q$ distributions in the data (points) and in the MC (histogram) for: (a) $pp$, (b) $\bar{p}p$ pairs, (c) unlike-sign ($p\bar{p}$) proton pairs. Dashed histograms represent the total background (misidentification + secondary interactions), filled histograms indicate the contribution to the background from secondary interactions.
Figure 3: (Left) Comparison of momentum distributions in the data (points) and mixed data sample (histogram) for (a) protons, (b) antiprotons. (Right) Distributions of the cosine of the angle between two particle momentum-vectors: (a) $pp$, (b) $p\bar{p}$ pairs. Points denote distributions for the data, histograms represent mixed data samples.
Figure 4: Distributions of particle four-momenta difference: (a) $pp$, (b) $\bar{p}\bar{p}$ pairs. Points denote distributions for the data, histograms represent mixed data samples.
Figure 5: Fits to correlation function distributions for $\bar{p}p$ pairs using the parametrisation described in the text: (a) event-mixed reference sample, (b) MC reference sample, (c) unlike reference sample.