6. DATA RECONSTRUCTION AND SELECTION

6.1 Data collection conditions

In the summer of 2000, two sets of electron triggered data were acquired. In the first set, the OTR was not included in the trigger whereas in the second it was. For this analysis we have used only the data from the second running period. We have selected those runs where only the Carbon (inner 2) target wire was inserted in the beam or those where both the Carbon and Titanium (below 1) target wires were inserted. The mean interaction rate of the selected runs was around 5 MHz.

For a general overview of the trigger, refer to section 3.5; below we only summarise the specific settings for the analysed data sample. The trigger for the electron channel made use of the ECAL pretrigger and SLT only. In 2000, the FLT was still in commissioning phase and was only used for counting the pretrigger candidates and forwarding them to the SLT. No filtering was done at the FLT level. The MUON pretrigger was operated simultaneously, but for this analysis we only use the ECAL triggered events.

The ECAL pretrigger selected clusters with:
– a transverse energy of the cluster $E_t > 1.0$ GeV;
– a transverse energy of the central cell of the cluster $E^c_t > \frac{1}{2} E_t$.

The pretrigger seeds were forwarded to the SLT. The momentum of the track was estimated from the energy of the ECAL cluster. Accepted clusters were combined into pairs and the invariant mass was determined. An invariant mass cut on the lepton pair of $2 \text{ GeV/c}$ was made at this level. The SLT used a simplified Kalman Filter requiring hits in the OTR-chambers after the magnet, to confirm and refine the lepton candidates. The surviving candidates were followed upstream through the magnet, and refined in a second Kalman Filtering step in the VDS.

A total sample of about 905,000 di-electron triggers was acquired using this scheme. The accepted events were reconstructed online and also off-line in several iterations.
6.2 Reconstruction

6.2.1 Reprocessing

The ongoing improvements in reconstruction software and in calibration and alignment made it necessary to reconstruct the data off-line in several reprocessing steps. For our analysis we use the result of the third reprocessing (rp003).

The reconstruction was done with the HERA-B software ARTE, consisting of several packages for stand-alone reconstruction in the different detector parts and packages to combine the information into a complete description of the reconstructed particles. For rp003, the version ARTE-03-09-r6 is used.

The first step in the reconstruction is the extraction of the hits from the raw data for every subcomponent. The next step is combining the hits into track segments. This is done stand-alone in the VDS and pattern tracker (PC). For the track segments in the VDS the software package Cats [66] is used. It is a cellular automaton specifically designed for the geometry of the VDS. The cellular automaton is also used for the reconstruction of segments in the pattern tracker[67]. There, for CPU time consumption reasons, it has replaced the old Kalman Filter package Ranger[68]. Ranger is still used for the extrapolation of the reconstructed PC segments through the MC[69] and TC chambers. For details on the tracking in 2000 see for example ref. [70].

The energy deposits in the ECAL are combined into clusters with a stand-alone cluster algorithm. After the stand-alone reconstruction, track segments and clusters are matched into long tracks. For the long tracks that have hits upstream and downstream of the magnet the momentum is calculated from the deflection in the magnet. The track parameters are refined in a refit on all hits associated with the long tracks.

The information from the SLT is used to determine which of the reconstructed tracks resulted in a trigger decision. A reconstructed track is assigned to each SLT message, based upon a $\chi^2$ depending on the differences in reconstructed and SLT track parameters in the OTR as well as in the VDS. For the comparison in the OTR, the track parameters at the point on the track closest to the magnet are used. For the comparison in the VDS, the track parameters of the first point of the track are used. The $\chi^2$ is defined as:

$$\chi^2 = \chi^2_{VDS} + \chi^2_{OTR},$$

with

$$\chi^2_{VDS,OTR} = \frac{\Delta x}{\delta x}^2 + \frac{\Delta y}{\delta y}^2 + \frac{\Delta r}{\delta z}^2 + \frac{\Delta \phi}{\delta r}^2,$$

(6.1) (6.2)
Δx is the difference between the VDS (OTR) and the SLT parameters; δx the estimated error. No reconstructed track is selected if χ2 VDS or χ2 OTR is larger than 55, for the track for which χ2 is minimal. We refer to reconstructed tracks assigned to the SLT messages as trigger tracks.

After the track reconstruction, the vertexing package Grover [71] is called, which combines VDS segments into reconstructed primary vertices. At least three VDS segments are required for the reconstruction of a primary interaction. The target positions are used as an input for the primary search.

### 6.2.2 Primary vertex and target position

To be able to separate prompt \( J/\psi \) from detached \( J/\psi \), we need precise knowledge of the primary interaction point and the position of the \( J/\psi \) vertex. Reconstruction of the track parameters of the particles is already adequately done in the general reprocessing, therefore this information is used in our analysis. The determination of the position of the primary vertex is also performed during reprocessing, however, due to the importance of this information to this analysis, this is redone.

There are two main reasons to perform the vertex reconstruction again. In the determination of the primary vertex using the GROVER package all tracks are used, including those from the \( J/\psi \) candidate. If the \( J/\psi \) originates from a B decay the primary vertex position will be biased, leading to a reduction in separation power.

Also, the positions of the target wires are used as seeds in the primary search. These positions are taken from the target database, which is not always correct. A better estimate of the target positions is obtained by making use of the primary vertex positions reconstructed in a first iteration. The Grover primary vertex search is performed again, excluding the two electron candidates and using the reconstructed target wire positions.

The target wire positions are calculated by performing a Gaussian fit on the positions of the primary vertices of the reprocessed data from a single run. Longer runs have been divided into sets of 1000 events (corresponding to 3-5 minutes of runtime). This is done in order to be able to follow the movement of the wire during the run. Figure 6.1 shows the primary positions for 1000 events, with the Gaussian fit superimposed. Figure 6.2 shows the positions of the wires versus time obtained in this way.
6. Data reconstruction and selection

Figure 6.1. Reconstructed primary vertex positions of 1000 events ($z,x$ position for vertical wire, $y$ position for horizontal wire). The distributions show a Gaussian shape, the width of the Gaussian is shown.

6.3 Event selection

A preselection of events was made, based on the multiplicity of VDS tracks in the event. For background events, the multiplicity is higher than for $J/\psi$ events, since the probability of triggering on a high multiplicity event is higher. Therefore, we require the events to have at most 50 reconstructed VDS tracks. Furthermore, we require two tracks of opposite charge (VDS-OTR-ECAL matches) with high $E_T$ ($>1$ GeV), with a reconstructed invariant mass $>1.5$ GeV/c$^2$ in the event.

For our selection of electron candidates we only use reconstructed tracks that were recognised as trigger tracks. For $b\bar{b}$ events it is highly possible that both $b$ quarks eventually produce high $p_T$ electrons, e.g. if one of the B decays was semi-leptonic and the other decayed into $J/\psi$. Therefore in $B \rightarrow J/\psi$ events, the probability of triggering the event on a track other than the two electrons from the
6.3. Event selection

$J/\psi$ decay is not negligible. We would be able to reconstruct the $J/\psi$ in those events if we selected all tracks instead of only those that resulted in a trigger. Because it would introduce new uncertainties in the measurement of the relative yield of prompt $J/\psi$ and $B \to J/\psi$ events, we decided not to do this. Events triggered on electrons that were not both the decay product of the $J/\psi$, will therefore only appear as background in the $B \to J/\psi$ selection sample.

To reduce the number of wrongly reconstructed tracks in our sample, we only select tracks with a minimal number of hits in the VDS (> 5) and OTR (> 10). Furthermore, for the selected tracks we require a transverse momentum $p_T > 0.8$ GeV/c.

To find the position of the $J/\psi$ vertex, a fit of the vertex is done for any combination of two selected tracks, again making use of the Grover package. The fitted vertex is required to have a $\chi^2$ with a probability $P_{\chi^2} > 0.025$. The distribution for $P_{\chi^2}$ is shown in figure 6.3.

In the case of multi-wire runs, for each selected combination of tracks one of the two wires is selected as most probable origin. For this selection we used the track parameters of the reconstructed $J/\psi$ candidate, extrapolated to the $z$ position of the wire and selected the wire which was closest in $x$ or $y$ (depending on the

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**Figure 6.2.** Reconstructed position of the wires. The $x$-axis shows an arbitrary number, increasing with increasing time of data taking. The movement of the beam in time can clearly be seen in the change of $x$ and $y$ position. Labels show which positions belong to the Carbon and Titanium wire.
direction of the wire). The probability for assigning the wrong wire is estimated from simulation to be less than 1%.

If more than one primary vertex is reconstructed, the one closest to the $J/\psi$ is selected as the primary interaction vertex. After the primary has been selected, it is checked that for both electron candidates the distance to that primary compared to the distance to any other primary is minimal. If not, the event is discarded. In this way we prevent background from events where the two electron candidates were produced with different origins.

The information about the event, including track parameters of all VDS segments, primary vertex and wire positions, and any combination of opposite sign trigger tracks, is stored in a root-file [72] for further analysis. The total number of stored events can be found in table 6.1.

### 6.4 Electron identification

Figure 6.4a shows the spectrum of the reconstructed mass of the two trigger tracks. With no additional cuts, there is no clear signal at the $J/\psi$-mass, though some enhancement can be observed. The picture can be improved by applying strong cuts on the identification of the tracks as electrons. For this we use two methods. With the first method, the particle is required to have lost part of its energy by bremsstrahlung in the detector material. This is typical for electrons. Of course, the lost energy should be recovered and taken into account correctly. As will be shown, this method is especially powerful in reducing the background.
6.4. Electron identification

<table>
<thead>
<tr>
<th>selection</th>
<th>number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>preselection: # VDS tracks &lt; 50,</td>
<td>468 k</td>
</tr>
<tr>
<td>2 tracks with opp. charge, $E_T &gt; 1$ GeV, mass &gt; 1.5 GeV</td>
<td></td>
</tr>
<tr>
<td>2 trigger tracks</td>
<td>315 k</td>
</tr>
<tr>
<td># VDS hits &gt; 5</td>
<td>314 k</td>
</tr>
<tr>
<td># OTR hits &gt; 10</td>
<td>303 k</td>
</tr>
<tr>
<td>$p_T &gt; 0.8$ GeV/c</td>
<td>277 k</td>
</tr>
<tr>
<td>$P_x^2$ of vertex &gt; 0.025</td>
<td>204 k</td>
</tr>
<tr>
<td>wire selection</td>
<td>202 k</td>
</tr>
</tbody>
</table>

Table 6.1. Number of remaining events after each selection step described in section 6.3. The total number of selected events is 202 k.

The second method of electron identification makes use of the relation between the energy and momentum ($E/p$), which should be about one for electrons.

6.4.1 Bremsstrahlung

Before entering the ECAL, some of the electrons have lost part of their energy through bremsstrahlung in their interaction with the material before the ECAL. Recovery of the bremsstrahlung energy is important for two reasons. Of course, the invariant mass spectrum of two electrons improves if the reconstructed momentum of the electrons is corrected for the effect of the energy loss. Also, requiring that the particle has radiated a bremsstrahlung photon can serve as an electron identification criterium. This significantly improves the signal to background ratio, though it also considerably reduces the signal, as will be shown.

To be able to correct the electron momentum, the emitted bremsstrahlung photon must be identified and its energy measured. We can identify three distinct regions in the detector where bremsstrahlung takes place: downstream of the magnet, upstream of the magnet, and inside the magnet.

The first region is of little interest, since the radiated photon travels in the same direction as the electron, depositing its energy at the same position in the ECAL. Its energy will therefore automatically be added to the electron cluster. The momentum measurement of the electron is also not influenced by the radiation, since it is determined from the bending in the magnet, before the radiation loss. Since there is no separate photon cluster, no additional electron identification is possible in this case.

If an electron radiates a photon upstream of the magnet, the photon will travel in a
Figure 6.4. Reconstructed invariant mass for all selected pairs of tracks: a) no bremsstrahlung requirement, b) bremsstrahlung cluster assigned to one or both tracks, c) both tracks assigned bremsstrahlung clusters. After applying the bremsstrahlung requirement the signal of the $J/\psi$ becomes visible around 3.0 GeV/c$^2$. 
6.4. Electron identification

Figure 6.5. Schematic view of the detector with an electron that radiates a photon before the magnet.

straight line, whereas the electron will be bent by the magnetic field. Extrapolating the reconstructed segment of the electron track in the VDS to the ECAL, one can determine the position of the photon cluster, as shown in figure 6.5. If a cluster is found at this position, the energy of the cluster is treated as bremsstrahlung energy of the electron candidate. Since the momentum of the electron is measured by the bending in the magnet, it is straightforward to obtain the corrected momentum \( p_{\text{corrected}} \) for the recovered energy loss:

\[
p_{\text{corrected}} = p_{\text{measured}} + E_{\text{photon}},
\]

where \( p_{\text{measured}} \) is the measured momentum of the electron and \( E_{\text{photon}} \) the reconstructed energy of the photon.

For radiation inside the magnet, the photon cluster will lie on the line between the extrapolated VDS-segment and the electron cluster. However, the correction for the momentum of the electron is not so straightforward anymore, even if the energy of the photon is recovered. The momentum is estimated through the total deflection in the magnet. The path of the electron will show a kink in the magnet at the position of the radiation, since the momentum of the electron decreases at that point. This is illustrated in figure 6.6. The correction applied to the measured momentum, required to get the momentum at the vertex, depends on the position
Figure 6.6. Bremsstrahlung inside the magnet. \( x_{\text{no rad.}} \) denotes the position where the electron would have entered the ECAL without radiation. If a photon is radiated inside the magnet, the radius of the curve that the electron describes \((r_1, r_2)\) decreases at the point of the radiation due to the lowered momentum. The effect on the measured momentum depends on the energy of the photon and on the position where the radiation takes place. This position can be determined by the position of the photon in the ECAL.

inside the magnet where the radiation took place. If the radiation took place just at the beginning of the magnet, the correction will be the same as in equation 6.3. The correction on the momentum will be smaller if the bremsstrahlung took place near the end of the magnet. The position where the radiation took place can be determined from the photon position in the ECAL. For small angles of deflection, the dependence of the photon position on the position of radiation is linear.

A first approximation of the corrected momentum is given by[73]:

\[
p_{\text{corrected}} = p_{\text{measured}} + \frac{x_e - x_{\text{ph}}}{x_e - x_x} E_{\text{photon}},
\]

where \(x_e\) is the \(x\)-position of the electron cluster, \(x_{\text{ph}}\) the position of the photon and \(x_x\) the position of the extrapolated VDS segment.

Figure 6.7 shows for MC the relative position of the bremsstrahlung cluster to the electron cluster \((x_e - x_{\text{ph}}/|x_e - x_x|)\). The three different regions can be clearly distinguished in this plot.

We can use bremsstrahlung photons originating from radiation upstream of and inside the magnet as electron identification. However, the background of uncorrelated ECAL clusters is larger in the second case, since the area in which a search for bremsstrahlung clusters is performed is larger. In this analysis we shall only use bremsstrahlung before the magnet for electron identification, but the momentum correction is applied for bremsstrahlung both before and inside the magnet.

In the di-lepton invariant mass spectrum we can require that at least 1 or both
6.4. Electron identification

Figure 6.7. MC: Relative distance \((x_e - x_{ph}/|x_e - x_x|)\) of the bremsstrahlung cluster to the electron cluster. Three regions can be defined: in front of the magnet \((z_{brem} < 230\,\text{cm})\), in the magnet \((230 < z_{brem} < 680\,\text{cm})\) and behind the magnet \((z_{brem} > 680\,\text{cm})\), with \(z_{brem}\) the position where the radiation took place.

electrons have radiated a bremsstrahlung photon to identify them as electrons. In the following we shall refer to no bremsstrahlung requirement as 012 BR, at least 1 bremsstrahlung as 12 BR and the requirement that both electrons have radiated a photon as 2 BR.

Figures 6.4b and c show the corrected di-electron invariant mass spectrum for the 12 BR and the 2 BR cases respectively. Comparing these figures with the 012 BR one (6.4a), we note a significant increase in the \(J/\psi\) signal to background ratio.

To estimate the number of wrongly assigned bremsstrahlung clusters, we search for clusters at \(x = x_x\), but with the ECAL mirrored in \(y\) \((y = -y_x)\), i.e. assuming the ECAL to be symmetric in \(y\). We refer to clusters assigned to tracks in this way as fake bremsstrahlung. The rate of these fakes is typically 10 % of the total bremsstrahlung rate.

Although the bremsstrahlung requirement is very effective in reducing the background, it has an efficiency of only about 35% per electron. As the number of detached \(J/\psi\) events is expected to be small, this reduction in efficiency is unacceptable and can therefore not be used in this case. We expect, however, that the
combinatoric (non electron) background will be significantly reduced due to the requirement of a detached vertex, so that there is no need for this extra identification (see chapter 8). The efficiency of the bremsstrahlung requirement ($\varepsilon_{\text{brem}}$) can be precisely determined from the data. We obtain the number of prompt $J/\psi$ with 012 BR by extrapolating the number in the 12 BR or 2 BR invariant mass spectrum, making use of $\varepsilon_{\text{brem}}$ (see section 7.2).

6.4.2 $E/p$ distribution

For electrons, the ECAL clusters contain all of their energy. Hadrons, on the contrary, only lose part of their energy in the ECAL. Therefore, by comparing the energy of the reconstructed ECAL cluster with the reconstructed momentum of the track, one can distinguish between hadrons and electrons. For electrons one expects the spectrum of energy over momentum ($E/p$) to be a Gaussian centred around one, whereas for hadrons the value of $E/p$ is generally smaller than one.

The $E/p$ spectrum for all trigger tracks is shown 6.8a. This spectrum is dominated by hadronic background. The fact that this spectrum is centred around 0.9 is artificial. Due to the $E_T$ cut at pretrigger level, high energy clusters are preferred. Furthermore the SLT-algorithm makes use of the assumption $E = p$ in the first tracking steps, therefore the rejection power is larger for tracks with $E/p$ far from one (see section 3.4).

By making use of electron identification via bremsstrahlung, we are able to select a much cleaner sample of electrons. In figure 6.8b the distribution is shown for triggered tracks identified as electrons by radiation in front of the magnet. The shaded histogram in figure 6.8b shows the $E/p$ distribution for tracks identified by fake bremsstrahlung, as described in section 6.4.1. After subtraction of this background, a distribution with a mean of 0.99 and a Gaussian width of 0.082 is obtained.

A comparison between the $E/p$ spectrum from the MC simulation and data is shown in figure 6.8c. The simulation predicts a width which is about 20% narrower than of the data. This can be explained by effects of misalignment and of noise in the ECAL, which are not adequately simulated.

For the determination of the total number of $J/\psi$ we apply a cut on $E/p$ in both data and MC. We require it to deviate less than $3\sigma$ from the mean of the distribution, where $\sigma$ is the respective measured Gaussian width of the distribution. After the cut on $E/p$, 122 k $J/\psi$ candidates remain.
6.4. Electron identification

Figure 6.8. a: data: $E/p$ distribution for all trigger tracks. b: data: $E/p$ distribution for tracks that have a bremsstrahlung cluster attached to them. The shaded histogram shows the spectrum for tracks that were identified with fake bremsstrahlung. c: $E/p$ distribution for Monte Carlo and data. The fake bremsstrahlung distribution has been subtracted from the data. The dashed lines show the Gaussian fits applied to data and MC.

\[
\begin{align*}
\text{mean}_{\text{data}} &= 0.99 \\
\sigma_{\text{data}} &= 0.082 \\
\text{mean}_{\text{MC}} &= 0.98 \\
\sigma_{\text{MC}} &= 0.055
\end{align*}
\]